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THE JOURNAL OF AGRICULTURAL SCIENCE

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AND THE ROTHAMSTED RESEARCH INSTITUTES BY

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THE VALUE OF MINERALOGICAL EXAMINATION IN DETERMINING SOIL TYPES, WITH A METHOD OF EXAMINATION AND A COMPARISON OF CER- TAIN ENGLISH AND SCOTTISH SOILS.

BY JAMES HENDRICK, B.Sc., F.I.C.,
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and University of Aberdeen.)*

(With One Text-Figure.)

INTRODUCTORY.

*Accounts have already been published by this department of investigations made as to the origin, nature and properties of the glacial drift soils of the north-east of Scotland; in particular, the soil as found at the Experimental Farm of Craibstone, near Aberdeen, has been studied by means of mechanical analysis and the determination of the chemical composition of the fractions resulting therefrom (1). The results obtained have brought out some characteristic features of the Craibstone soil, and have indicated that important differences may exist between a glacial drift soil, derived mainly from rocks of granitic nature, and such a soil as that of Rothamsted, arising from the "Clay with flints" formation.

It has been shown that the soil of Craibstone consists of granitic and schistose material, mechanically ground down by ice action, comparatively little chemical action having taken place. The coarser fractions, as well as the finer, still contain reserves of such bases as lime, magnesia, potash and soda. In contrast to this, the material of the Rothamsted soil has been subjected to prolonged chemical action, and consists mainly of the end-products of weathering such as quartz, aluminium silicate, and oxides of iron, the bases mentioned having been almost completely removed from all except the finest mechanical fractions.

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Such differences as these between soils are significant from the agricultural point of view, and it is important to have a ready means of recognising them.

The ultimate chemical analyses of the mechanical fractions, such as were recorded in Part I of "Studies of a Scottish Drift Soil(1)," are very tedious to perform, and, if a number of samples sufficient for comparison are to be examined in reasonable time, a more expeditious method must be adopted. Investigations have therefore been carried out along mineralogical lines, in an endeavour to discover to what extent a system of mineralogical analysis can be made use of in classification, and the results are recorded in the present paper.

In seeking for methods of solving the many and complex problems of the soil, investigators have given much attention to the mechanical and chemical composition of the soil, but comparatively little to its mineralogical composition, at any rate in this country. In France M.M. Delage and Lagatu(2), and M. Chaveaux(1) have discussed the constitution of soils from the mineralogical standpoint, and advocated the microscopic examination of soils as an important aid to our knowledge of soil conditions.

M. Dumont(3) in 1905 described methods of analysis in which, after cleaning with oxalic acid and removal of the silica with ammonia solution, the clay was separated by centrifuging, the material remaining fractionated by means of heavy liquids, again with the aid of the centrifuge. The results were checked by microscopical examination.

In America, McCaughey and Fry(5) have given an account of the methods of mineralogical separation and examination, and illustrated the application of these by giving analyses of several soil types.

Recently there has been published in Germany by Dr Franz Steinriede(7) a second edition of *Anleitung zur Mineralogischen Bodenanalyse*, where details as to the methods of examination are given, with an introductory survey of the work of the leading investigators.

That the methods of mechanical and chemical analysis have their limitations, as a means of estimating the relative values of soils, is well recognised, and it may be said that the defects of mineralogical analysis are equally serious. It seems evident, however, that information of value ought to be obtainable from a knowledge of the mineral composition of the soil. Minerals and their alteration and decomposition products form the basis of the soil, and it seems reasonable to infer that its physical and chemical properties are, to some extent at least, determined by the particular minerals present and their relative abundance. From

a knowledge of the mineralogy, the chemical elements present can be ascertained, and, further, what is of equal importance, their mode of combination. As a ready means of supplying this additional information, a mineralogical analysis is, in this respect, superior to a chemical one.

A knowledge of the mineral constituents of the soil is especially useful in the case of the class of which the Craibstone soil is a typical example. Here the soil arises more or less directly from the "living" rock. Although derived from glacial drift, there has been little resorting of the rock material, and the soil is a residue from weathering of all the minerals which constituted the original fresh rock. Material in solution has been removed in the natural drainage, but the decomposition products of the minerals have not been removed bodily as in the case of a soil whose material was originally derived from rocks of sedimentary formation. Much of the "drift" of the north-east of Scotland is very thin, and there is a direct relationship between fresh materials of the geological formation of the district and the material of the soil derived therefrom.

The results of the examination of a glacial soil, given by Merrill(6), may be referred to in this connection. Details are given of the mineral constitution of the mineral separates of a mechanically fractionated soil, and there follows a bulk analysis of the air-dried material. "Such a soil," he concludes, "is plainly little more than a highly quartose granite or gneiss in a pulverulent condition. *Its composition could have been almost foretold by the microscopic examination.*" The same remark might be made of Craibstone soil.

THE SOILS EXAMINED.

While Craibstone soil is representative of a large area in the north-east of Scotland, it is only one of many types found in the district, and the same may be said of the Rothamsted soil in relation to English types. For the purposes of this paper, soils were examined from a number of different localities and representative of a number of different types. Samples were obtained from three research stations in England, the soils of which have already been studied by laboratory methods, and by field and pot experiments, so that their characteristics are well known. The other samples examined were obtained from a number of different formations in the north-east of Scotland. A short description follows of each of the soils made use of in these investigations.

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Rothamsted Experimental Station. Strong flinty loam, from the "clay with flints" drift formation which covers much of the chalk plateau of Hertfordshire. The samples¹ examined were from Broadbalk and Harpenden Fields.

Woburn Experimental Station. Light sandy loam, from Lower Greensand formation (thin drift in places). Sample¹ from Stackyard Field.

Olympia Agricultural Co., Offchurch, Leamington. Medium loam, from thin drift overlying Keuper Marl (New Red Sandstone). Sample¹ from Field 6.

Rose Farm, Cromarty. Deep and fertile light loam, subsoil sandy, overlying thick substratum of red boulder clay. Old Red Sandstone lies below¹.

Balmakewan Farm, Marykirk, Kincardineshire. Medium loam, from drift, overlying Old Red Sandstone.

Aulton Farm, Cruden Bay, Aberdeenshire. Regarded locally as heavy soil and commonly called "clay." Derived from quartzose metamorphic and granitic drift overlying rocks of same nature.

Craibstone Experimental Farm, Aberdeen. Free-working loam, from granitic drift overlying granite and quartzose gneiss.

Craigour Farm, Glassel, Aberdeenshire. Light sandy loam (locally called "haugh" land), from glacial lacustrine deposit, derived from granitic material.

Laighmuir Farm, Insch, Aberdeenshire. Medium loam, from thin drift derived mainly from underlying igneous rock, which belongs to syenite type and contains less quartz than granite.

Berrybrae, Insch, Aberdeenshire. Medium loam, same derivation as "Laighmuir" but with admixture of diorite rock type, which is more basic than syenite.

Dunnydeer Farm, and Auchinbradie Farm, Insch, Aberdeenshire. Good working loams (locally called "sharp" loams). From thin drift derived mainly from underlying basic igneous rock of olivine gabbro type (no quartz).

METHODS OF INVESTIGATION.

The soil was air-dried and sieved in the usual way, the "fine earth" passing the 3 mm. sieve being subjected to mechanical analysis, preparatory to mineralogical examination. The "fine gravel," "coarse sand"

¹ These samples were obtained through the kindness of Sir E. J. Russell, Dr Voelcker, Dr Crowther, and Sir T. H. Middleton respectively, to whom we wish to acknowledge our indebtedness.

and "fine sand" so obtained were each further sub-divided quantitatively into three mineral groups by means of heavy liquid solutions and the use of the electro-magnet, the main object being to isolate the quartz from the other minerals and to divide the silicates into two groups, those rich in potash and soda, and those rich in iron, calcium, and magnesium. The three groups thus obtained have been designated the Orthoclase Group, the Quartz Group and the Ferro-silicate Group. As will be explained later, it was not found practicable to make a satisfactory quantitative separation of the "silt," "fine silt" and "clay," but with the exception of the last, all grades were examined microscopically and the predominant and characteristic minerals present determined.

Table I. *Mechanical analyses of soils. Results as percentages of "fine earth" dried at 100° C.*

	Broadbalk Field	Harpenden Field	Offchurch Field 6	Woburn Stackyard Field	Balmakewan	Rose Farm, Cromarty	
Fine gravel ...	1.98	3.92	2.29	1.88	5.56	2.23	
Coarse sand ...	5.47	7.26	58.69	44.80	27.19	39.77	
Fine sand ...	22.85	22.25	10.76	17.71	22.23	28.45	
Silt ...	28.55	30.50	10.40	14.46	19.06	13.24	
Fine silt ...	16.23	16.34	6.26	12.83	9.66	7.58	
Clay ...	15.77	12.87	8.88	5.41	7.52	4.04	
Ignition loss ...	4.58	5.20	3.52	4.07	9.20	5.17	
Solution loss (by difference)	4.57	1.66	—	—	—	—	
	100.00	100.00	100.80	101.16	100.42	100.48	
	Aulton	Craibstone	Craigour	Laighmuh	Berrybrae	Dunnydeer	Auchinbradie
Fine gravel ...	3.50	6.23	4.22	6.43	7.62	10.11	10.45
Coarse sand ...	17.64	32.57	16.76	24.45	31.61	26.30	23.05
Fine sand ...	24.80	26.71	20.87	30.30	23.16	20.42	18.81
Silt ...	13.85	6.64	18.87	16.57	14.26	9.86	12.89
Fine silt ...	22.69	12.93	24.52	11.30	11.48	19.74	17.71
Clay ...	9.25	5.47	2.64	1.46	1.85	2.83	2.95
Ignition loss ...	8.01	9.72	11.53	10.00	9.15	10.95	12.55
Solution loss (by difference)	.44	—	.59	—	.87	—	2.59
	100.00	100.27	100.00	100.51	100.00	100.21	100.00

Mechanical analysis. This was performed according to the official method of the Agricultural Education Association and the results given in Table I were so obtained. In the case of certain of the English soils, where carbonate of lime was known to be present, samples were also prepared without treatment with dilute hydrochloric acid.

Heavy liquid separation. This was performed on the mechanical fractions after they had been ignited to remove organic matter. Bromoform, whose specific gravity is 2.9, was found to be a convenient heavy

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liquid with which to work. In making the separation a simple glass separating-funnel was used. This had a diameter of 10 cms. at the upper margin, and an internal diameter of 1 cm. at the neck. It was fitted with a stop-cock, the bore of which was nearly as wide as that of the neck-tube. The internal surface of the funnel must be thoroughly cleaned and dried before use, and the bromoform used must be of high purity.

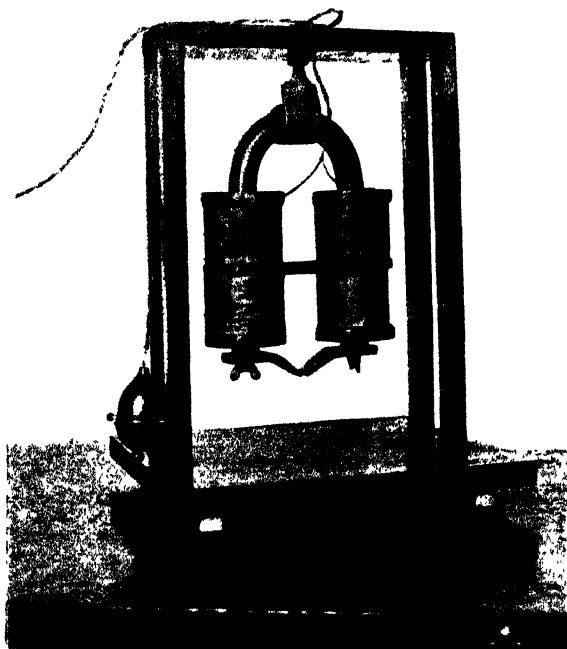
The soil fraction to be treated is first dried in a steam-oven, and then placed in the funnel and the bromoform poured in. The material is thoroughly stirred and then allowed to stand until separation has taken place. When the heavy minerals have settled, they are run out with a quick turn of the stop-cock, and collected on a filter paper fitted in a funnel, placed ready in a bottle to receive the bromoform draining off. The filter funnel may then be transferred to another bottle and the grains left on it washed with benzene and dried. Similarly the material lighter than the bromoform can be collected, washed and dried. The mechanical fraction has now been divided into two, one part containing minerals of specific gravity above 2.9, and the other, those below this. It is usually found necessary to repeat the operation once or twice to ensure satisfactory purity of separates, especially in the case of the fine sand. The heavy portion will be found to contain practically all the calcium and magnesium bearing minerals, known as the ferro-magnesium silicates, and along with these the oxides of iron. This constitutes Group 3, the Ferro-silicate Group.

It remains to separate the quartz from the lighter portion. To do this, bromoform is diluted with benzene until a mixture is obtained in which a grain of quartz (s.g. 2.65) will just sink, while one of orthoclase feldspar (s.g. 2.56) floats. This mixture is used just as the pure bromoform was, and the portion which sinks is found to consist almost entirely of quartz and constitutes Group 2, the Quartz Group. In the portion of specific gravity less than 2.65 the predominant mineral is generally the potash feldspar, orthoclase, and this portion constitutes Group 1, the Orthoclase Group.

In practice it is found that some high specific gravity minerals tend to find their way into the group of lower density. This may be because they are partially weathered, whereby the density is lowered, or because they are of flaky habit, like biotite, when surface tension counteracts the force of gravity. It is therefore found necessary to supplement heavy liquid separation by separation by magnetism.

Separation by magnetism. Magnetite is the only iron mineral commonly met with in soils that is sufficiently strongly magnetic to be

attracted by an ordinary horse-shoe magnet, but, by the use of a sufficiently powerful electro-magnet, most of the iron-bearing compounds can be separated from iron-free compounds. Thus the common rock-forming minerals, the ferro-magnesium silicates, may be separated from such minerals as quartz and felspar. By varying the intensity of the magnetic field, electro-magnetic minerals, when in a state of purity, can be sub-divided into several groups. The use of the electro-magnet is familiar to petrologists in dealing with sands and crushed rocks, and, within certain limits, it may be employed to advantage in analysing soils.



Electro-magnet.

The type of electro-magnet used is illustrated in the accompanying photograph. The coils are sufficient to give resistance suitable for use with a 220 volt lighting system. The poles of the magnet are fitted with flat pieces which can be adjusted laterally. By narrowing or widening the space between these pole pieces, the intensity of the magnetic field can be increased or diminished. The whole magnet is hung on a wooden

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framework as figured. The connecting wire to the electric supply is furnished with a switch by means of which the current can be turned on or off easily and quickly as required.

In removing the electro-magnetic minerals it is found convenient to place the portion of separate to be treated on a small piece of thin cardboard. This is brought in close proximity to the pole pieces, the current switched on, and the card moved lengthwise and crosswise under the tips of the poles until these are covered with attracted material. The card is then replaced by a small dish or tray and the current switched off. The grains are, for the most part, released, but residual magnetism retains a few which require to be brushed off. The material remaining on the card is again worked over and the operation repeated until no more grains are attracted to the magnet. The material so separated is treated again, as it is generally found that some non-magnetic material has been caught up along with the magnetic.

The electro-magnet was found very useful in separating from the Orthoclase Group such minerals as biotite, which, as already explained, was not perfectly separated from the group by the heavy liquid method. Similarly, partially weathered ferro-magnesian such as augite and hornblende could be removed from the Quartz Group. Also, in the group of minerals of density greater than 2.9, the non-magnetic minerals could be isolated, if desired, from the ferro-magnesian silicates, etc. It was not found practicable, however, to sub-divide the electro-magnetic minerals themselves, at any rate quantitatively. Even in the fine sand, individual grains are not composed entirely of one mineral. A grain consisting almost entirely of a mineral of certain magnetic strength may include, or have attached to it, a minute particle of a mineral of higher magnetism. Such a compound grain is thus attracted to the magnet much more readily than a pure grain, and this at once upsets an attempt at strict quantitative separation. This question of complex grains affects also the heavy liquid separation, but in that case it is not so vital, for the specific gravity of the compound particles will be determined usually by the larger component, and hence the grain will be found, as a general rule, in the group of the dominant component.

Undisintegrated fragments—granite, schist, sandstone, etc., occurring chiefly in the fine gravel of some soils were grouped as rock fragments. These might have been crushed before separations were made, but the fine gravel was not of sufficient importance to warrant this.

Microscopic examination. The mineral groups were all examined under a petrographic microscope. The material was not prepared in any way

beyond occasional treatment with dilute hydrochloric acid, if the particles were badly stained with iron, etc., and crushing of the larger grains in the "fine gravel" and "coarse sand." The samples were mounted in clove oil as a medium and the constituents identified by the usual optical tests applicable to mineral fragments.

THE MINERAL GROUPS.

The Orthoclase Group. In the soils dealt with this group was usually composed almost entirely of the two potash-bearing feldspars, orthoclase and microcline. Along with these the potash-bearing mica, muscovite, was also grouped. There are, of course, numerous other rock-forming minerals whose specific gravity would bring them into this group, such, for example, as analcite, sodalite, leucite, nepheline, but these are not commonly preserved in soils unless the parent rock is rich in the particular mineral.

The Quartz Group. Along with the quartz, heavier members of the lime series of feldspars occur, but not in great quantity. They are seldom associated with quartz in igneous and metamorphic rocks, and, in the case of rocks of sedimentary origin, they are small in amount because they are readily weathered. With quartz are included other forms of silica, such as flint, jasper, etc. Calcium carbonate occurs in this group, and, when present, can be estimated by weighing before and after treatment with dilute hydrochloric acid.

The Ferro-silicate Group. This is a much more complex group mineralogically, but from the agricultural standpoint, the matter is considerably simplified because such common rock-forming minerals as the pyroxenes and amphiboles are predominant. These belong to the ferro-magnesian minerals and though several species are recognised, yet in a general way, *pure* mineral species are not found, and they may be regarded as silicates of alumina with varying amounts of iron, magnesium and calcium. Next to the ferro-magnesians in abundance come the oxides of iron—haematite, limonite and magnetite, while olivine is another common rock-forming mineral found in this group. In composition it is a silicate of magnesium with varying amounts of iron and lime and weathers readily to serpentine, a hydrated silicate of magnesium. Other minerals which may be mentioned in this group, are the rarer "accessory" rock-forming minerals such as epidote, garnet, zircon, tourmaline, and apatite. With the exception of apatite these are all highly resistant to weathering, and are, on that account, unimportant agriculturally, though interesting

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mineralogically. The case of apatite is entirely different, as it is the only common phosphate-bearing mineral found in rocks.

The results of the mineralogical analyses are given in Table II.

Table II. *Results of mineralogical analyses as percentages of ignited mineral matter.*

Locality			Orthoclase Group			Quartz Group*			Ferro-silicate Group		
			Fine gravel	Coarse sand	Fine sand	Fine gravel	Coarse sand	Fine sand	Fine gravel	Coarse sand	Fine sand
a	Broadbalk Field	...	nil	nil	trace	29.4	85.0	95.3	70.5†	15.0†	4.7
	Harpenden Field	...	nil	nil	trace	58.4	85.8	94.7	41.6†	14.2†	5.3
	Offchurch Field 6	...	nil	7.6	3.0	33.9	89.9	94.0	66.0†	2.4†	3.0
	Woburn, Stackyard Field		nil	nil	6.2	56.7	97.3	90.4	43.0†	2.7†	3.4
b	Rose Farm, Cromarty		nil	13.7	14.9	77.2	82.2	78.8		4.1	6.2
	Balmakewan	...	10.6	12.9	17.5	31.8	78.2	72.8		8.8	9.7
c	Aulton	...	39.0	15.1	13.4	34.5	71.8	76.1		13.0	10.5
	Craibstone	...	17.7	22.9	13.6	76.4	73.0	70.4		4.1	15.9
	Craigour	...	63.7	14.8	39.6	31.3	62.0	42.5		23.2	17.8
	Laighmuir	...	36.3	54.3	21.1	25.9	22.9	41.4		22.7	37.4
d	Berrybrae	...	56.1	51.3	20.5	21.7	18.3	32.0		30.4	47.5
			Plagioclase						Mainly rock fragments		
	Dunnydeer	...	51.0	62.0	65.5	trace	nil	nil		38.0	34.5
	Auchinbradie	...	20.8	36.0	38.8	trace	nil	nil		64.0	61.1
Averages											
a	English soils	...	nil	—	2.3	44.6	89.5	93.6	55.3†	8.6†	4.1
b	Scottish sedimentary	...	5.3	13.3	16.2	54.5	80.2	75.8	—	6.4	7.9
c	Scottish quartz-bearing igneous	...	42.6	31.7	21.6	37.9	49.6	52.5	—	18.7	25.8
d			Plagioclase								
	Scottish basic igneous		35.9	49.0	52.1	trace	nil	nil	—	51.0	47.8

* Calcium carbonate found in Section a included in Quartz Group.

† Mainly oxides of iron.

DISCUSSION OF THE RESULTS OF THE MINERALOGICAL ANALYSES.

Fine Gravel. Little importance need be attached to the percentage figures of this fraction. In the first place, in most of the soils examined, it is a relatively small proportion of the whole, though it is to be observed that it takes a more important place in the Scottish soils than in the English, particularly in the basic igneous soils of Dunnydeer and Auchinbradie. Secondly, the grains of the fine gravel have not, in many cases, been reduced to single minerals. In the soils from igneous and metamorphic rocks this is particularly true, the percentage of original rock fragments in these being considerable.

The *Orthoclase Group* is not represented in any noteworthy quantity in any of the English "fine gravels," whereas in the Scottish soils it is very prominent. In the soils of basic origin containing no quartz the feldspar is mainly of the plagioclase or lime variety.

The Quartz Group is present in the sedimentary soils from both countries. In the Rothamsted soils it is mostly in the form of flint. In the Scottish soils, arising from igneous rocks, the proportion is dependent on the acidity of the parent rock. Thus it is highest in the granitic soil of Craibstone and Aulton, while in the basic rocks from Dunnydeer and Auchinbradie it is absent except for traces introduced through slight admixture with metamorphic material.

The Ferro-silicate Group forms a point of strong contrasts between the soils of the two countries. In the English examples it consists practically entirely of oxides of iron, while in the Scottish there is a mixture of ferro-magnesian silicates.

Coarse Sand. This grade also may contain composite fragments, but in such, one mineral is usually distinctly predominant and the material has been classified accordingly.

The Orthoclase Group is poorly represented in the English soils and this forms a point of contrast between these and the Scottish soils of sedimentary origin, as well as those of igneous derivation. Traces only of potash felspar were noted on microscopic examination of the Rothamsted soils.

The Quartz Group. In passing from the fine gravel to the coarse sand it will be noticed that in the English soils there is a distinct increase in the proportion of quartz, whereas in the Scottish soils this is either not so marked or does not occur at all. This is accounted for by the difference in origin and history. Prolonged attrition and re-sorting has eliminated most of the larger quartz grains in the sedimentary rocks, thereby reducing them to the "coarse sand" grade. In the Scottish rocks attrition has had much less play, the result being that the quartz becomes graded more or less according to the relative proportions of the larger and smaller crystals in the original rock.

The Ferro-silicate content is lower in the coarse sand than in the fine gravel of the English soils examined. This is contrary to the general rule for the ferro-silicate group whose content is usually higher the finer the grade of material. It is to be noted, however, in the case of the soils under consideration, that the ferro-silicate group in the fine gravel and coarse sand consists mainly of oxides of iron. The proportion of these oxides is higher in the fine gravel than in the coarse sand, and it is on this account that the ferro-silicate content as a whole is higher in the fine gravel. In the Scottish soils ferro-magnesian silicates constitute most of the ferro-silicate group in the coarse sand, the iron oxides being subordinate.

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Fine Sand. It is only when the fine sand is examined that the real significance of the origin of the soil is brought out.

The Orthoclase Group content again brings into contrast the English and Scottish types. The highest figure among the English soils occurs in the case of the Woburn soil, where 6.2 per cent. is reached. In the Scottish representatives the lowest is found in the Aulton soil with 13.4 per cent. The high content of the Scottish soils of sedimentary origin, as compared with that of the English ones, is interesting when the history of the parent rocks is taken into consideration. The Scottish rocks are of Old Red Sandstone formation, which is believed to have accumulated rapidly in shallow waters near the coast line, the materials being derived from granitic and metamorphic rocks rich in felspar. On the other hand the parent rocks of the soils of the south-east of England were formed much more gradually and in deeper waters. The material was more thoroughly weathered and sorted out, with the result that only refractory minerals such as quartz persist in any considerable proportion.

The Quartz Group. If the quartz percentage is considered and the soils arranged in sequence accordingly, it is found that the English soils come first, beginning with the Rothamsted types containing about 95 per cent. and ending with Woburn soil containing over 90 per cent. Then there is a big drop between this and the Scottish types with 79 per cent. and 73 per cent.

The remaining Scottish soils of igneous origin occur in the order of the acidity of the original rock—first the granitic types, followed by the intermediate syenites and diorites (Craigour-Berrybrae) and finally the basic types (gabbro) of Dunnydeer and Auchinbradie.

The Ferro-silicate Group. With regard to this group, the soils of basic igneous origin are naturally the richest. Following these come the intermediate and more acid types, then the Scottish sedimentaries, while again there is a break between these and the English samples. Furthermore, there is a contrast in the *composition* of the ferro-silicate group, between the Scottish and English soils. In the latter the oxides of iron are again more abundant than in the former, and the proportion of the rarer "accessory" minerals (such as zircon and tourmaline), compared with the common rock-forming minerals (biotite, hornblende) is higher. In the Scottish soils it is these common minerals, the potential sources of plant food supply, which are predominant.

The Silt and Fine Silt were not analysed quantitatively because it was not found practicable to utilise the heavy liquid method of separa-

tion for material of so fine a grade. The action of gravity on the minute particles is unduly interfered with by surface tension and the viscosity even of so mobile a liquid as bromoform. The electro-magnet, however, can be used to concentrate the ferro-silicates. With some soils the silt and fine silt cake together on being dried and require to be triturated in water or very dilute acid before examination. When examined under the microscope, the nature of the minerals in much of the silt and fine silt can be determined and it is found that the same mineral species are represented as in the fine sand. The proportion of ferro-silicates is naturally greater, but quartz is generally still the most outstanding mineral, while oxides of iron are also conspicuous.

NOTES ON STATE OF PRESERVATION OF MINERALS.

The Orthoclase Group. The comparatively fresh appearance of the feldspar in the Craibstone soil has already been commented on, and this condition is equally characteristic of the other Scottish soils studied. In many cases the crystallographic faces could be recognised and numerous instances of cleavage surfaces with fresh pearly lustre were noted. In the smaller particles the microscope showed that many of the potash feldspars were turbid with decomposition products (kaolinisation) but a remarkable number were clear and "fresh" in aspect. In the English soils the proportion of decomposed to "fresh" fragments was higher than in the Scottish.

The plagioclase feldspars do not show the same turbid appearance, especially in the soils from Dunnydeer and Auchinbradie. The pronounced cleavage development in feldspars tends to the formation of angular fragments, but where this mineral is present in English examples (as from Offchurch) rounded grains are numerous, while in the Scottish soils they are inconspicuous. In the finer grades rounding is naturally not developed to the same extent.

Muscovite is apparently fairly resistant to chemical weathering and was present in most of the soils with the exception of those from basic igneous rock (Dunnydeer and Auchinbradie).

The Quartz Group. In the Scottish soils where quartz is present it is characterised by its rough angular appearance, the grains being bounded by curved fractured surfaces. Rounded grains are exceptional in the Scottish types, but in the English soils they are much more in evidence, finding their maximum development in the Woburn soil, where they constitute the bulk of the quartz in the fine gravel and coarse sand, and have a highly polished appearance. They have all the appearance of

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having been subjected at some time to wind action, when attrition under dry conditions produces its maximum effect. In all the soils a good deal of milky quartz was present, recognisable under the microscope by its numerous dust-like inclusions of minute fluid cavities. As with the feldspar, the rounding of the particles is not conspicuous in the grades below the coarse sand in any of the soils.

The Ferro-silicate Group. In this group the common ferro-magnesian rock-forming minerals are represented by one or more species in all the soils examined, sometimes one being predominant, sometimes another. These are remarkably fresh even in the soils of sedimentary origin. Hornblende and biotite are most commonly present. Augite does not seem to be so resistant to weathering, and was only found in noteworthy amount in the basic rock soils. The rhombic pyroxene, hypersthene, was more prevalent though at no time very conspicuous, except in the cases just mentioned. Chlorite, an alteration product from the ferro-magnesian, was noted on occasion, and serpentine was abundant in the soils of Dunnydeer and Auchinbradie, the parent rocks of these being rich in olivine.

The rarer "accessory" rock-forming minerals are present in surprising amount in the sedimentary soils. They owe their prevalence to their resistant nature, becoming concentrated in material which has been subjected to prolonged weathering and has accumulated from a variety of sources. In the Scottish soils of igneous origin where the material has been drawn more or less from one source of supply, the presence or absence of "accessories" will depend on their development in the particular rock from which the soil was formed. Epidote, garnet, tourmaline, zircon were the most common of the accessory minerals, all being quite fresh in appearance. Epidote and garnet were in granular form, but tourmaline, and especially zircon, though sometimes fragmentary, showed crystalline form. The zircons had the usual terminal pyramid faces finely developed in many cases. Garnet was conspicuously developed in the Balmakewan soil which is derived mainly from garnetiferous schists. Haematite and limonite were present in all the soils examined, the haematite occurring in rounded grains and amorphous masses, the limonite mostly as pale yellow scaly aggregates. Magnetite was present in varying amount in all the soils, sometimes quite unaltered, sometimes more or less altered to red iron oxide.

CHIEF MINERALS NOTED IN FINE SAND, SILT AND FINE
SILT IN APPROXIMATE ORDER OF ABUNDANCE.

Rothamsted. Quartz, haematite, limonite, magnetite, biotite, chlorite, epidote, hornblende, tourmaline, zircon, orthoclase, rutile, garnet.

Woburn. Quartz, haematite, limonite, biotite, tourmaline, epidote, magnetite, hornblende, garnet, zircon.

Offchurch. Quartz, haematite, limonite, magnetite, orthoclase, biotite, chlorite, hornblende, epidote, tourmaline, zircon, garnet.

Rose Farm. Quartz, orthoclase, hornblende, biotite, muscovite, garnet, magnetite, haematite, limonite.

Balmakewan. Quartz, orthoclase, biotite, hornblende, garnet, muscovite, plagioclase, tourmaline, zircon, magnetite, haematite, limonite.

Aulton. Quartz, orthoclase, biotite, muscovite, hornblende, haematite, limonite, magnetite, garnet, tourmaline.

Craibstone. Quartz, orthoclase, microcline, biotite, hornblende, muscovite, plagioclase, magnetite, epidote, garnet, tourmaline, haematite, limonite.

Craigour. Quartz, orthoclase, biotite, hornblende, muscovite, plagioclase, magnetite, haematite, limonite, (diatoms).

Laighmuir. Quartz, orthoclase, biotite, hornblende, muscovite, hypersthene, plagioclase, magnetite, haematite, limonite.

Berrybrae. Quartz, orthoclase, biotite, hornblende, plagioclase, magnetite, haematite, limonite.

Dunnydeer and Auchinbradie. Plagioclase, hypersthene, olivine, augite, biotite, serpentine, haematite, limonite, magnetite, apatite, zircon.

SUMMARY AND CONCLUSIONS.

1. The method of mineralogical analysis of soils is discussed as a useful means of examination for the purposes of classification, and references are made to certain investigations which have already been carried out on mineralogical lines.

2. Brief descriptions are given of the soils analysed for the purpose of this paper. The English samples were obtained from well known research stations, while the Scottish samples are representative of different soil types found in the north-east of Scotland.

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3. The methods of analysis are as follows:

A mechanical analysis is first made and the resulting "fine gravel," "coarse sand," and "fine sand," after ignition, are further separated by means of the heavy liquid bromoform, into three mineral groups.

(1) The Orthoclase Group characterised by potash felspar.

(2) The Quartz Group characterised by quartz.

(3) The Ferro-silicate Group characterised by ferro-magnesian silicates and iron oxides.

The electro-magnet and the petrological microscope are employed to assist in obtaining good separations into these three mineral groups.

4. The minerals commonly occurring in each group are noted and the results of mineralogical analyses of the soils examined are tabulated.

5. The results of the analyses are discussed, the English and Scottish types being compared with regard to constitution of the three mineral groups. It was found that the soils examined, all more or less of "glacial drift" origin, differed considerably in mineral content. This depended on the nature of the rock from which the "drift" was derived. Soils arising from "glacial drift," originally of sedimentary formation were generally composed almost entirely of quartz with comparatively small amounts of silicates, while, at the other extreme, soils of which the original material was of basic igneous formation contained almost no quartz and were rich in silicates.

The results of microscopic examination of the minerals as found in the soils examined are given with tabulation of the chief species in the "fine sand," "silt" and "fine silt."

6. By means of the methods of separation described, combined with microscopic examination, it has been found possible to contrast mineralogically certain English and Scottish soil types. For this purpose the "fine sand" obtained by mechanical analyses proved most useful.

7. The work recorded in this paper indicates that a short mineralogical examination affords a useful method of grading soils according to the reserve of bases which they contain in the form of silicates, and of distinguishing those which have little such reserve, of which Rothamsted soil may be taken as a type, from those which have rich reserves of the principal bases required by plants, of which Craibstone soil may be taken as typical.

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THE DETERMINATION OF THE NUMBER OF BACTERIA IN SOIL.

(PRELIMINARY COMMUNICATION)

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(With three Plates and five Figures.)

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INTRODUCTORY.

WYANT (1921) has recently reviewed the present status of the technique for bacterial counts by means of the plate method. The works of Reinke (1880) and Coplans (1912) seem to have escaped the attention of soil bacteriologists. Russell (1921) has pointed out the resemblance of the "soil colloids" to the nutrient jellies of the bacteriologist, and Söhnngen

(1913) has studied the effects of colloids on bacterial growth, but the necessity for the peptisation of the soil gels in order to obtain a representative bacterial suspension has not been recognised.

EXPERIMENTAL.

The medium employed in the following investigations was asparagin-mannite-salts agar, as used at Rothamsted, of the following composition:

K_2HPO_4	1.0 gm.	$CaCl_2$	0.1 gm.	Asparagin	0.5 gm.
KNO_3	0.5 „	KCl	0.1 „	$FeCl_3$	0.002 „
$MgSO_4$	0.2 „	NaCl	0.1 „	Agar	15.0 gms.
Distilled water 1 litre.					

The salts, together with the agar and water, melted in the steamer. Filtered through cotton wool. Mannite (1 gram) added. Standardised to P_H 7.3 using brom-thymol blue as indicator. Tubed in 10 c.c. lots and sterilised for 15 minutes at 15 lbs. in autoclave (Thornton, 1921).

I. AN EXAMINATION OF THE USUAL PLATE METHOD.

(1) *The effects of prolonged shaking and of the addition of beads.* A sample was weighed out for a moisture determination and then 25 gm. of soil were gently triturated in a mortar with a small quantity of the shake medium (Thornton, 1921), consisting of

Sodium chloride	5 gm.
Magnesium sulphate	1 gm.
Distilled water	1000 c.c.

previously sterilised in the autoclave.

The turbid liquid was poured off into a sterile glass-stoppered bottle which was marked at the 250 c.c. level. The muddy residue was again triturated with a small quantity of the medium and the operation repeated till all the soil had been worked down to a cream and washed into the bottle. Medium was then added to the mark, so giving a dilution of 1 in 10.

The bottle was then placed in a mechanical shaker of the inverted pendulum type making 100 cycles per minute, and shaken for 160 minutes. At the end of this period 2.5 c.c. samples were withdrawn by means of a clean sterile pipette and added to each of two bottles, containing 247.5 c.c. shake medium. Sterile glass beads were added to one of the bottles. Both bottles were then placed in the shaking machine, and 10 c.c. samples were withdrawn after a further 160, 320, and 1280 minutes respectively.

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The 10 c.c. lots were delivered into sterile glass bottles each containing 90 c.c. of the shake medium, and mixed by hand shaking. A repetition of these operations gave a dilution of 1 in 100,000. Duplicate plates were poured from the 1 in 10,000 and 1 in 100,000 dilutions, 1 c.c. being used for inoculating in each case. The plates were incubated at 22° C. and examined daily. The results are shown in Table I.

Table I.

Time of shaking 1 : 1000 dilution in minutes	Colonies							
	Without beads				With beads			
	Days incubated				Days incubated			
	2	3	4	5	2	3	4	5
160	{ 19	60	101	121	10	120	131	163
	{ 18	43	132	170	13	42	84	96
320	{ 27	79	106	157	14	38	57	111
	{ 5	41	76	164	13	38	51	98
1280	{ 47	70	134	166	12	20	47	62
	{ 38	71	122	131	5	12	26	36

It was found that the prolonged agitation had not exercised any appreciable influence over the counts obtained, but in the presence of beads had caused an undoubted reduction. This was so marked that it was not considered necessary to continue the incubation any further.

Conclusions. (a) The addition of beads to the 1:1000 dilution is apparently of no value, as a great reduction in the number of colonies results from their use.

(b) Prolonged shaking, *i.e.* from 5 to 24 hours, has little effect on the numbers.

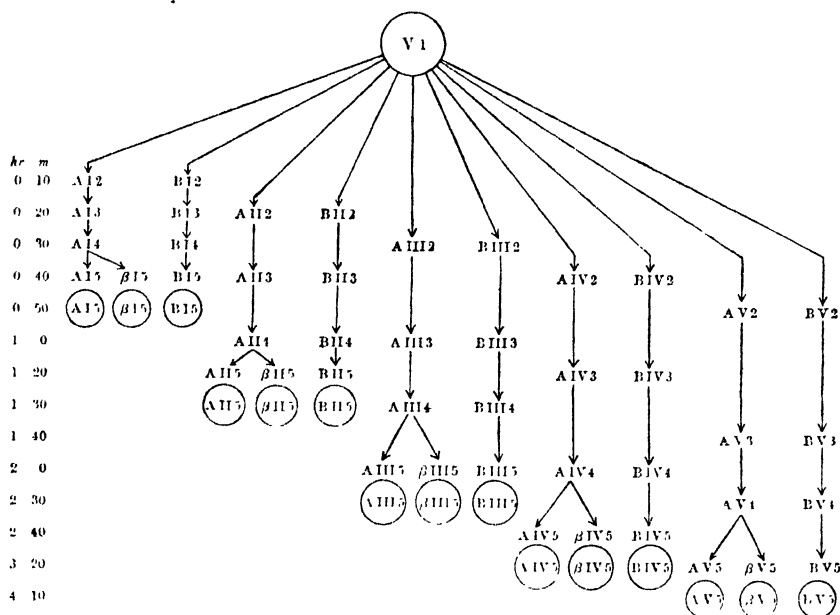
(2) *Influence of time of shaking and of the addition of beads to the 1 : 100 and to the 1 : 100,000 dilutions.* Twenty-five grams of soil were weighed out under sterile conditions and triturated in a mortar as in the last experiment. The turbid liquid was poured into a sterile bottle and made up to 250 c.c. as before. This bottle was labelled V 1, and placed in the shaker. At intervals of 10 minutes further amounts of 25 c.c. were withdrawn and added to bottles I 2, II 2, III 2, IV 2 and V 2 in duplicate, the one lot (A) containing 225 c.c. shake medium, the other (B) containing a measured volume of beads in addition to the 225 c.c. shake medium.

In series I dilutions were made at intervals of 10 minutes.

“	II	“	“	“	“	20	“
“	III	“	“	“	“	30	“
“	IV	“	“	“	“	40	“
“	V	“	“	“	“	50	“

In order to avoid confusion, a detailed time-table of the operations was drawn up in advance on a blackboard, each operation being erased after completion. The times for the pouring of plates are indicated by circles. A stop-watch was used to measure the actual times of shaking.

Table II.



In the last dilution two series were made from the A-4 dilutions, β indicating the addition of beads. Triplicate plates were poured.

The counts are shown in Table III.

Table III. Count on 10th day.

	Series A		Series B		Series β
	No beads		Beads, 2nd dil.		Beads, last dil.
Set I, at 10 mins.	(1) 1213		390		1543
50 mins.	(2) 1204	120	332	35	1350
	(3) 1306		342		1477
Set II at 20 mins.	(1) 484		501		495
100 mins.	(2) 540	50	lost	4.5	475
	(3) 502		422		457
Set III at 30 mins.	(1) 515		487		368
150 mins.	(2) 387	50	471	5.5	355
	(3) 557		622		520
Set IV at 40 mins.	(1) 508		570		545
200 mins.	(2) 592	55	327	4.5	385
	(3) 586		496		601
Set V at 50 mins.	(1) 480		469		337
250 mins.	(2) 436	45	589	5.0	334
	(3) 386		435		324

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Conclusions. (a) Beads in the second dilution have caused a significant decrease, even with the shortest period of shaking.

(b) A longer shake than 50 minutes causes a decrease, either with or without beads.

(3) *The effects of different periods of shaking, and of the addition of beads or silt to the 1 : 100,000 dilution.* The last experiment was repeated with the following modifications:

(1) Periods of shaking were only one-fifth of those previously employed.

(2) The addition of beads to the second dilution was omitted.

(3) Three parallels were made from the fourth dilution. One received nothing, beads were added to the second, and silt to the third.

The counts obtained after 10 days' incubation are given in Table IV.

Table IV. *Count on 10th day. Millions per gm. moist soil.*

Actual nos. of colonies			Approximate means			Time shaken minutes	Total time in contact with liquid (mins.) (including 10 mins. trituration in mortar)
Soil alone	Beads	Silt	Soil	Beads	Silt		
15	8	80	3	2	6	10	45
60	22	44					
22	25	69					
(267)	352	260	27	38	34	20	70
238	390	313					
318	411	433					
(261)*	336	538	50	34	49	30	100
528	(192)†	430					
467	lost	508					
280	332	404	34	34	40	40	115
352	308	455					
374	386	329					
332	326	293	30	(33)	26	50	135
253	(105)†	236					
323	(71)†	243					

* Moulds.

† Spreaders.

Conclusions. (a) The addition of beads is of no value, the highest count with beads being less than in the case of the soil alone. Silt appears to have no appreciable effect.

(b) Highest counts are given with 30 minutes' shaking, further shaking causing a reduction. This is in agreement with the results of other workers.

(c) There is a continuous change in the type of colony predominating at each period of shaking. This leads to the conclusion that two opposed processes are at work—one of disintegration of soil particles giving an increase in numbers, and the other a destruction of organisms, probably as a result of the attrition of the soil particles against each other, the action resembling that of a ball-mill.

From the above considerations it is clear that the ordinary method of shaking for a definite period or a given number of times is not satisfactory.

(4) *Range of deviation with a uniform treatment.* Forty grams of soil were weighed out, triturated, and made up to 400 c.c. as in previous experiments. This was shaken for 30 minutes, and then eleven subsamples, of 25 c.c. each, were withdrawn and each added to 225 c.c. as usual. Ten of these lots were replaced in the shaker, the other was shaken by hand a few times and dilutions made at once. Five plates were poured (Set 0).

The others were diluted at intervals of 30 minutes and five plates poured from the 1 : 100,000 dilution.

The time that elapsed between pouring the first plate of Set I and the last plate of Set X was about $1\frac{1}{2}$ hours, so that an allowance of 2 minutes can be made per plate. The counts obtained on the tenth day are shown in Table V.

Table V. *Count on plates in Exp. 4 on 10th day.*

Plate	1	2	3	4	5	Mean
Set 0	297	433	344	260	338	334
I	339	294	368	295	395	338
II	243	293	346	351	237	294
III	327	321	288	291	317	309
IV	170	298	369	333	319	298
V	219	252	355	272	207	261
VI	335	291	263	237	369	299
VII	219	309	275	313	303	284
VIII	293	373	255	438	312	334
IX	242	203	278	218	137	216
X	184	196	131	177	145	167

It is clear that the means of the Sets 0 to VIII inclusive all agree so far as the first significant figure, 29 observations giving 300, 9 giving 400 and 7 giving 200.

(5) *The effects of different shake media.* Five 25 gm. lots of soil were weighed out from a carefully bulked sample, and placed in sterile mortars. Each was then gently triturated with one of the following media:

- A. Distilled water.
- B. 0.2 % NaCl + 0.025 % Na_2CO_3 .
- C. 0.2 ,, + 0.05 ,,
- D. 0.5 ,, + 0.1 MgSO_4 .
- E. 0.85 ,,

The thick cream so obtained was, in each case, transferred to a sterile bottle and the operations repeated until all the soil had been

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washed into the bottle. The volume was made up to 250 c.c., and the bottles shaken for 2 minutes in the mechanical shaker. Dilutions of 25 c.c. to 225 c.c. fresh media were made, each being shaken for 2 minutes.

Plates were poured from the 1 : 10,000, 1 : 100,000 and 1 : 1,000,000 dilutions, the colonies on the first being uncountable. The counts obtained on the tenth day are shown in Table VI.

Table VI.

Dilution	A Distilled water	B 0.2 % NaCl 0.025 % Na ₂ CO ₃	C 0.2 % NaCl 0.05 % Na ₂ CO ₃	D 0.5 % NaCl 0.1 % MgSO ₄	E 0.85 % NaCl
1 : 100,000	{ 47 105 30	110 143 184	197 172 100*	29 86 23	57 47 54
1 : 1,000,000	{ 4 7 11	9 8 28	15 16 20	4 6 5	8 7 3
Mean, in millions per gm. moist soil	6.5	15	16.5	5	5.5

* Spreaders.

The addition of sodium carbonate evidently had a significant effect.

II. DIRECT EXAMINATION BY THE MICROSCOPE.

(1) *Direct smears.* Lumps of moist soil were broken by hand, and the freshly-exposed surface lightly rubbed on a clean slide. After air-drying, the slide was flamed, allowed to cool, and then stained for 1 to 3 minutes with 1 per cent. rose Bengal in 5 per cent. phenol, washed carefully with water, dried, and then either mounted with Canada balsam in xylol, or examined at once with a 1/12 in. oil immersion. The latter method has the advantage that the crystals of quartz are practically invisible.

It was found as the result of the examination of a large number of slides prepared in this way, that the soil organisms occur almost entirely in colonies which are always embedded in a jelly-like material. They are not attached to the surfaces of sand grains, or to mineral crystals, smaller specimens of which are universally present. The colloidal material stains deeply with malachite green, is stained brown by purple iodine, is insoluble in dilute acid, but is dissolved by alkalies. It also appears to form a continuous film over most, if not all, of the discrete particles. It is concluded that this material consists for the most part of colloidal silica, that is, silicic acid gel.

Counts of the colonies, or of the organisms, over a measured area of a smear would probably be of value for comparative purposes, but the difficulty of standardising such counts in terms of a given mass or volume of soil is a formidable one. A direct volume determination is not admissible, for this neglects all the larger particles which have not remained adherent to the glass. Direct weighing of the smear fails for the same reason, with the further disadvantage that the weight of soil in question is so small.

(2) *Direct counts by films.* Ten grams of soil were triturated with sterile distilled water in a clean sterile mortar to a cream and the volume made up to 100 c.c.

After shaking by hand for a minute or so, samples of 0.01 c.c. of the muddy liquid were withdrawn by means of a calibrated capillary pipette and dropped on clean slides which had been stored in absolute alcohol. The slides were placed over pieces of paper on which areas of 1, 2, or 4 sq. cm. had been marked. The drops were then carefully spread so as to obtain as even a film as possible over the area. It was found that an L-shaped spreader whose lower limb was slightly convex, and 2 cm. long, was the most satisfactory. After air-drying, the films were flooded with a very dilute solution of collodium (ordinary collodium solution 1 part, ether 14 parts, alcohol 5 parts) as recommended by Oehler (1911). As soon as the ether had evaporated, a few drops of rose Bengal in phenol were cautiously added, care being taken not to break the film by allowing the drops to fall from any height. After staining for 3 minutes, the surplus stain was drained off, and the preparation carefully washed. [It is in this operation that the greatest care is required, the film being very easily broken. One can, however, generally be sure of five or six satisfactory films out of every 10 preparations.]

After air-drying the preparation was mounted in Farrant's medium. Canada balsam was not satisfactory. Organisms were counted under the $\frac{1}{12}$ in. oil immersion.

A typical count is shown in Table VII. A square-mesh (5×5) micrometer was used and the tube length adjusted so that the edge of each mesh measured exactly 10μ on a Zeiss stage micrometer. Then each field will have an area of $(50)^2$ sq. μ or $(.005)^2$ sq. cm. = .000025 sq. cm. Now .01 c.c. was spread over 4 sq. cms., i.e. an area of 1 sq. cm. represents .01 c.c. of suspension,

\therefore an area of 1 sq. cm. represents $\frac{.01}{4}$ c.c.,

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\therefore an area of $\cdot 000025$ sq. cm. represents $\frac{\cdot 01 \times \cdot 000025}{4}$ c.c.,

i.e. $\frac{\cdot 00000025}{4}$ c.c.

Suppose, to eliminate fractions, we consider 16 times this quantity, we obtain $\cdot 000001$ c.c. or one millionth part of a cubic centimetre.

The original suspension, however, contains 0.1 gm. soil per c.c. Hence the number of organisms in sixteen fields \times ten millions will give the number per gram of soil.

Table VII.

											11 to 20	21 to 40	41 to 60	61 to 80	81 to 100	Clumps	Individuals
14	3	.	2	.	.	.	.	.	.	.	.	.	.	.	.	19	28
2	2	3	1	.	1	.	.	.	3	1	.	.	.	.	.	13	70
.	4	2	1	.	1	.	.	.	.	.	.	.	.	.	.	8	24
3	.	.	2	2	1	.	1	1	1	.	.	.	.	.	.	11	54
4	1	2	.	.	.	.	.	.	.	.	.	.	.	.	.	7	12
2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	2
5	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	7	10
6	2	.	1	1	.	.	1	.	.	.	.	.	.	.	.	11	27
2	1	.	1	.	.	.	.	.	.	.	.	.	.	.	.	4	8
8	.	.	2	.	.	.	1	.	.	.	.	.	.	.	.	11	24
18	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	19	20
4	2	.	3	.	.	.	.	.	.	.	.	.	.	.	.	9	20
.	1	1	.	2	.	.	.	.	1	.	.	.	.	.	.	5	25
4	1	1	.	.	.	1	.	.	.	.	.	.	.	.	.	7	16
2	2	2	3	.	.	.	1	.	1	.	.	.	.	.	.	11	42
2	.	2	.	.	1	.	.	.	.	1	.	.	.	.	.	6	29
.	5	.	1	1	.	.	1	.	.	1	.	.	.	.	.	9	42
1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	3
3	2	.	1	1	.	.	1	.	1	.	.	.	.	.	.	9	34
1	1	1	.	.	.	.	.	.	1	2	.	.	.	.	.	6	46
.	1	.	1	.	.	.	1	.	2	2	.	.	.	.	.	7	64
.	3	.	.	.	1	.	2	.	.	2	.	.	.	.	.	8	58
3	3	1	.	1	.	.	.	.	1	.	.	.	.	.	.	9	27
1	3	.	2	3	.	.	.	.	.	2	.	.	.	.	.	11	60
.	1	.	2	.	.	.	.	.	.	2	1	.	.	.	.	6	70
1	6	3	2	1	.	.	1	.	.	1	1	.	.	.	.	16	88
5	3	.	3	.	.	.	.	.	1	1	.	.	.	.	.	13	48
.	3	2	1	.	.	.	1	.	.	.	.	.	.	.	.	7	24
2	.	.	1	2	.	.	.	.	1	3	1	.	.	.	.	10	101
5	2	1	.	.	.	.	.	.	.	.	.	.	.	.	.	8	12
3	2	.	.	1	.	.	1	.	.	.	.	.	.	.	.	7	20
4	1	2	1	.	1	.	.	.	.	1	.	.	.	.	.	10	52
3	1	1	2	1	.	.	.	1	.	2	.	.	.	.	.	11	60
1	2	1	3	1	1	.	1	.	.	.	.	.	.	.	.	10	39
4	4	1	2	.	2	.	.	.	3	.	.	.	.	.	.	16	65
6	2	.	.	1	.	.	.	.	.	.	.	.	.	.	.	9	15
2	2	.	.	1	1	.	1	.	.	.	1	.	.	.	.	8	55
12	1	.	2	.	.	.	.	.	1	.	.	.	.	.	.	16	32
3	1	1	2	.	.	1	1	.	.	.	.	.	.	.	.	9	31
1	2	.	2	.	.	.	.	.	.	.	.	1	.	.	.	6	63
.	1	.	.	1	.	.	.	.	1	1	1	.	.	.	.	5	62
.	2	.	1	.	.	1	.	.	.	.	1	.	.	.	.	5	45

Table VII (*continued*).

1	2	3	4	5	6	7	8	9	10	11 to 20	21 to 40	41 to 60	61 to 80	81 to 100	Clumps	Individuals
8	.	.	1	.	2	.	1	.	.	.	.	.	.	.	12	32
1	2	.	1	1	1	.	.	.	2	.	.	.	.	.	8	40
3	1	2	2	1	1	.	.	.	.	2	.	.	.	.	12	60
3	1	.	.	.	.	.	.	.	1	1	.	.	.	.	6	30
.	1	.	1	1	.	.	.	.	.	.	.	.	.	.	3	11
4	1	.	2	3	.	.	1	.	1	1	.	.	.	.	13	62
.	4	1	.	1	1	.	.	1	.	1	3	.	.	.	12	136
4	1	.	.	1	1	1	1	.	1	1	1	.	.	.	10	71
8	.	2	3	1	2	1	1	.	1	1	1	.	.	.	21	113
4	1	2	.	2	.	.	1	.	1	.	.	1	.	.	12	90
2	1	5	.	.	1	.	.	.	.	.	.	.	.	.	9	25
2	.	.	.	.	.	.	.	.	.	1	.	.	.	.	3	17
1	2	.	1	.	1	.	.	.	.	.	.	.	.	.	5	13
3	3	1	2	1	.	.	.	.	.	1	.	.	.	.	11	40
9	2	1	1	.	.	.	.	.	.	.	.	.	.	.	13	20
2	2	.	.	.	.	.	.	.	1	1	.	.	.	.	6	31
3	2	.	.	2	.	.	.	.	1	.	.	.	.	.	8	27
2	.	.	.	.	.	.	.	.	1	.	.	.	.	.	3	12
.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	1	4
4	.	1	1	1	.	.	.	.	.	.	.	.	.	.	7	16
1	1	.	.	.	.	.	.	.	1	3	.	.	.	.	6	58
8	2	.	.	1	.	.	.	.	.	1	.	.	.	.	12	32
2	.	.	.	2	.	.	1	.	.	1	.	.	.	.	6	35
2	.	.	1	.	1	.	.	.	.	.	.	.	.	.	4	12
1	.	.	1	2	.	.	.	.	1	.	.	.	.	.	5	25

Total for 67 fields

214 103 43 63 40 20 5 21 3 29 36 12 2 . . 591 2639

Mean for 16 fields 141 630

i.e. 6300 millions per gram of soil.

The method is of course subject to a large experimental error. The difficulty of deciding whether a particle is an organism or not is not avoided, dead organisms (provided they have not been dead for some time) may take the stain; anaerobes and other organisms which will not grow on the medium will be counted, but on the other hand probably many spores and smaller organisms will pass unnoticed. It was found that good illumination was a necessity. A gas-filled opalite lamp gave the best results.

The numbers obtained—thousands of millions and upwards—are in excess of previous estimates, as revealed by the usual methods which apparently break down since they do not effect the dispersion of the colloidal gels in which the colonies are embedded.

Conn's method (1918) for direct counts was found to be practically unworkable with a clay soil.

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III. PLATE COUNTS AFTER VIBRATION.

Mr W. B. Hardy, F.R.S., pointed out to the author that the motion imparted by an ordinary shaking machine was not of the type required for the efficient dispersion of the soil particles, and suggested that if a trembling vibratory motion of the correct amplitude (probably small) and frequency (probably high) could be imparted to the suspension, dispersion would be rapid. After several trials the following procedure was adopted. The apparatus is shown in Fig. 1. The clean sterile Winchester *A* contained 2 litres of the sterile shake medium (0.2 per cent. NaCl and 0.05 per cent. Na_2CO_3). This passed through the long siphon (previously sterilised in autoclave) provided with a screw clip to the vibrator vessel *B*, consisting of a short broad tube having a side opening, the capacity of the vessel being 100 c.c. The lower end of the tube was fitted with a rubber ring so as to make a water-tight joint with the celluloid cover of an ointment jar. A second rubber ring was slipped over the joint for additional security. The hammer of an electric bell played on the celluloid membrane, whose vibrations were thus imparted to the liquid directly. A rubber bung carried by a retort clamp served as a convenient method for the control of the amplitude of the hammer; it was found that by the adjustment of the bung and of the make and break contact screw the surface of the liquid could be maintained in a state of violent agitation. The sound emitted resembled the hum of a bee. The side-opening was closed by a rubber bung through which passed a delivery tube leading to a sterile Winchester; the opening of this tube was oblique, so as to expose a large area of cross section. By adjusting the rate of flow so that the passage of two litres took place in not less than 20 minutes, the surface of the liquid in the vessel was continuous with that in the delivery tube, so ensuring that in the event of particles or organisms tending to be concentrated at the surface of the liquid in the form of a film they would be continually removed by the flowing liquid.

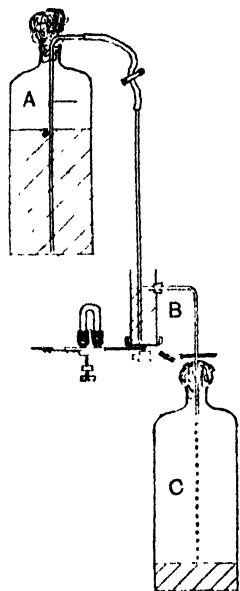


Fig. 1. Arrangement of apparatus (diagrammatic)

(1) *Comparison of the electrical vibrator with ordinary shaking by hand.*

(a) A gram of Fen soil, in which smears had shown large numbers of

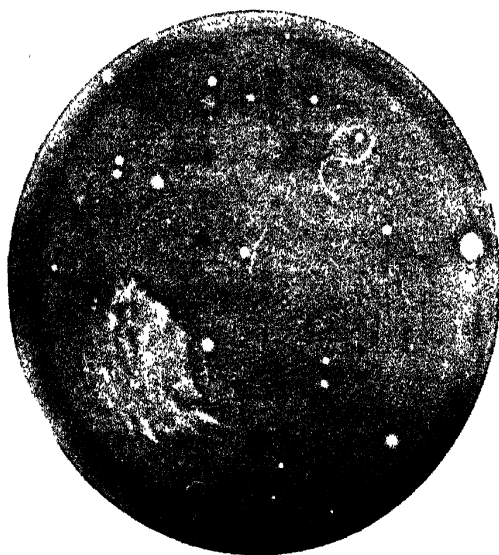


Fig. 2. Dilution 1:100,000. Shaken by hand.

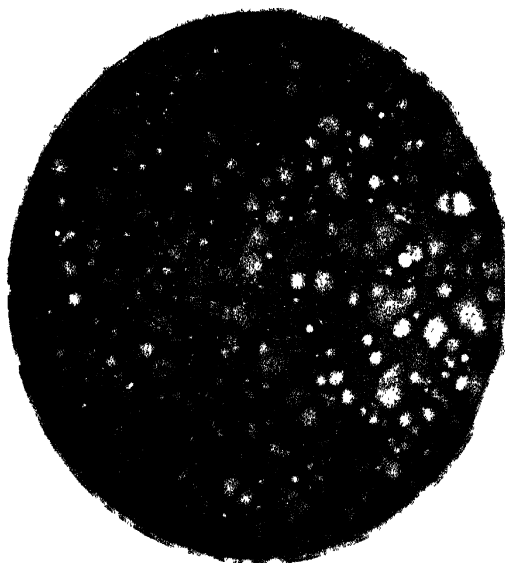


Fig. 3. Dilution 1:100,000. Vibrated.

organisms to be present, was triturated with a small quantity of the shake medium and ultimately made up to 400 c.c. After shaking for 5 minutes by hand, 10 c.c. were withdrawn by a sterile pipette and added to 240 c.c. shake medium so giving a dilution of 1 in 10,000. After thoroughly shaking by hand, 25 c.c. were withdrawn and added to 225 c.c. shake medium, and these operations repeated. Plates were poured in triplicate from the 1 : 100,000 (10^5) to the 1 : 10^{12} dilutions inclusive, by steps of 1:10.

(b) A gram of the same soil was placed in the clean and sterile vibrator vessel, the shake medium allowed to siphon slowly through, so that the passage of the 2 litres was complete in about 30 minutes. The resultant milky, opalescent suspension was shaken by hand to ensure thorough mixing and then 40 c.c. withdrawn and added to 160 c.c. shake medium so giving a dilution of 1 : 10,000. Further dilutions were made as usual up to 1 : 10^{12} , and plates poured in triplicate from each.

Table VIII.

<i>Shaken by hand</i>		<i>Vibrated</i>	
Dilution 1 : 100,000		Dilution 1 : 10,000,000	
109	} Mean 9.8 millions	23	} Mean 250 millions
85		28	
99		25	
Dilution 1 : 1,000,000		Dilution 1 : 100,000,000	
15	} Mean 11 millions	2	} Mean 300 millions
9		2	
9		5	
<i>i.e.</i> 10 millions per gram.		<i>i.e.</i> 250 millions per gram.	

From the counts of the two series after 15 days' incubation shown in Table VIII, it is obvious that vibration is far more efficient than trituration combined with hand-shaking. In both series the higher dilutions were sterile. Typical plates from the 1 : 100,000 dilution after 4 days' incubation are shown in Plate I, figs. 2 and 3, the photographs for which were prepared by using the petri as a negative.

(2) *Technique of method finally adopted.* The counts obtained in the last experiment, though a great advance, are still very much below the range of the direct count. Also, small crumbs of soil were found in the vibrator vessel, pointing to incomplete disintegration.

The following modifications were made:

(i) A trace of gelatine (about 0.1 per cent.) was added to the shake medium prior to sterilisation to serve as a protective colloid.

(ii) The soil sample was thoroughly, but not violently, triturated in a mortar to a cream and made up to a definite volume as in the first experiments. A clay soil was used.

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(iii) Instead of carrying out the higher dilutions by steps of 1:10 by hand, each step of 1:1000 was effected by means of the vibrator.

The result was satisfactory. On the fourth day the colonies on all dilutions below the 1:10¹¹ were uncountable, the figures for this being 113, 88, and 97, or an average of 100, that is, 10 billions per gram. Further, there were no "slow-growers." All the colonies attained their maximum size in 4 days, and although the plates were kept under observation for over a month, there was no further increase in numbers. Typical plates are shown in Plate II, figs. 4 and 5. The possibility of the diluents having been contaminated had to be considered. The experiment was repeated, using the same procedure as before, but with a slightly reduced amplitude of vibration, and controls were poured from each bottle of diluent immediately before use, the same pipette being used to effect the inoculation.

On the fourth day the counts of the 1:10¹¹ dilution gave 303, 230, and 276 colonies, or an average of 27 billions per gram of moist soil¹. Typical plates are shown in Plate III, figs. 6 and 7. All the controls were sterile.

For the convenience of other workers, full experimental details are appended.

(a) *Shake medium.* Stock solution of

NaCl	10 per cent.
Na ₂ CO ₃	2½ "

in distilled water.

For use 50 c.c. of the stock solution were made up to 4 litres with distilled water, and two sheets of gelatine added. Sterilised in the autoclave for 20 minutes at 15 lb. Clean dry Winchesters, marked at the 2 litre level, were plugged with cotton wool and sterilised in the hot air oven for at least 4 hours. When cool, the bottles were filled up to the mark with the sterile medium and replugged. One of these was still sterile after having stood for two months. The hydrogen ion concentration was measured by the electrical method² and found to be P_H 8.33. 10 c.c. required one drop of decinormal acid to discharge completely the colour with phenolphthalein.

(b) *Sterilisation.* The sterilisation of the vibrator vessel and connection tube was carried out as follows: The celluloid membrane was removed, together with the outer rubber ring, and after thoroughly washing in

¹ This figure is greatly in excess of the result of the direct count p. 27—6,300 millions per gram. The discrepancy is probably due to continued division during the interval between weighing and plating, which was about 2 hours. The presence of gelatine in the shake medium may have served as a source of energy.

² The author is indebted to Mr F. W. Foreman, M.A., for this determination.

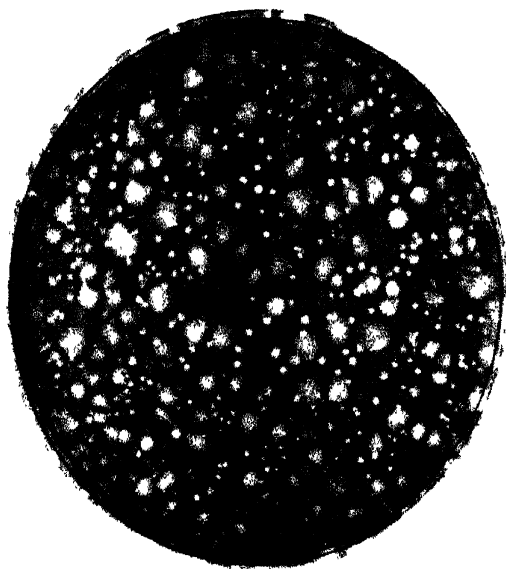


Fig. 4. Dilution 1:10,000,000,000.

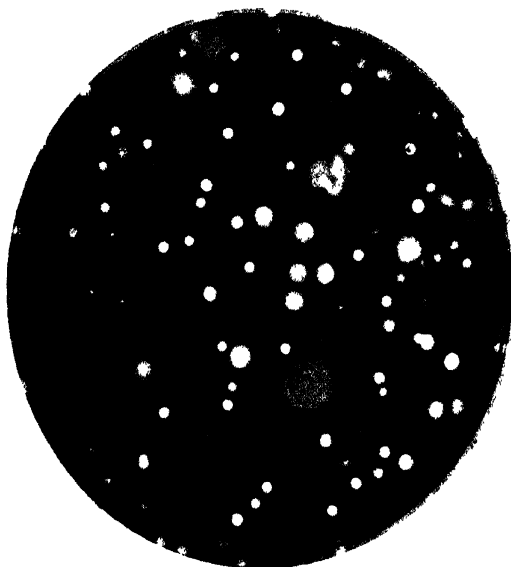


Fig. 5. Dilution 1:100,000,000,000.

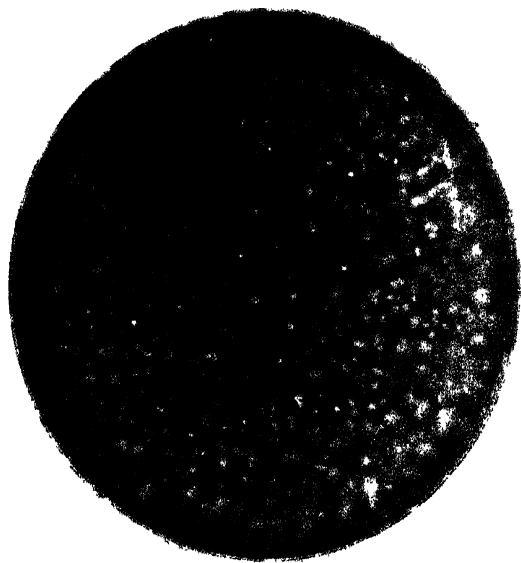


Fig. 6. Repeat. Dilution $1 : 10,000,000,000$

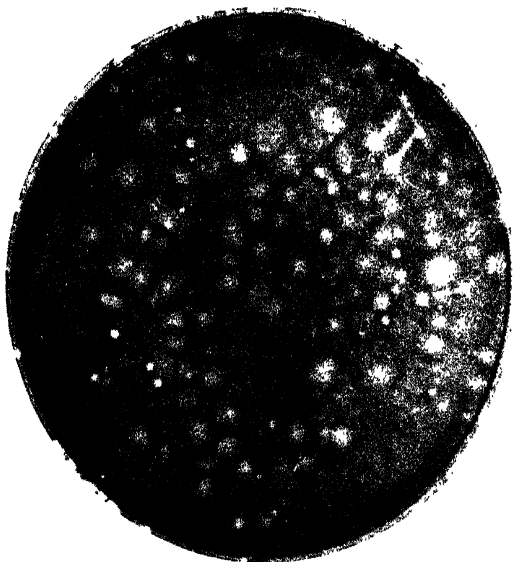


Fig. 7. Repeat. Dilution $1 : 100,000,000,000$

running water under the tap, rinsed with a solution of bleaching powder to which a drop of hydrochloric acid had been added; it was again washed thoroughly in running water, then with a dilute solution of sodium thiosulphate, and again with distilled water; finally with some of the sterile shake medium. The tube connections underwent the same treatment. This not only applies to the preliminary sterilisation but to the cleaning between each stage of dilution. Petri dishes, and pipettes, were sterilised in the hot air steriliser as usual.

(c) *Technique.* Twenty-five grams of soil were weighed out as rapidly as possible and placed in a clean sterile mortar. A small quantity of the shake medium was added, and the whole worked up to a cream by gentle trituration. The turbid liquid was poured off into a sterile stoppered bottle bearing a mark at the 250 c.c. level, and the residue treated with more of the shake medium, the operations being repeated till all the soil had been washed into the bottle which was then filled up to the mark. The bottle was shaken to mix thoroughly the contents and 2 c.c. withdrawn while the liquid was still in motion, a sterile pipette being used, and the sample transferred to the vibrator vessel, which was about half filled with shake medium. The vibrator was started and the screw-clamp on the rubber siphon tube opened. [The control plates of the first bottle of diluent were poured before the commencement of operations, and the control plates of the second bottle of diluent poured during the process of the first dilution.] As soon as the first step of dilution was completed, the vibrator vessel was washed and sterilised, and the operations repeated, 2 c.c. of the suspension in the Winchester being added to the vibrator vessel.

The process was again repeated thus giving a dilution of 1 : 10¹⁰. From this plates were poured, 1 c.c. being used for one set and 0.1 c.c. for a second.

It is not suggested that this technique is necessarily all that can be desired. No doubt there is an optimum range of both amplitude and frequency which requires to be determined exactly. A protective colloid may be found which does not possess the disadvantage of serving as a source of energy for bacterial growth.

The conditions must be standardised in all respects if the results of different workers are to be comparable. Reinke's apparatus has the great advantage that both frequency and amplitude remain approximately constant, but the shrill penetrating note renders its adoption undesirable unless a sound-proof room is available. On this account an electrical or mechanical method seems the more promising.

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No application of the method has so far been made, and as circumstances have arisen which may render it impossible for the author to proceed with the investigations at present, it was considered advisable that the results obtained should be presented at once.

IV. A PHYSICO-CHEMICAL INVESTIGATION.

The preceding experiments having suggested that bacterial counts obtained by the usual methods might be rather a measure of the "degree of dispersion" of the soil particles than of the number of bacteria present, it was decided to repeat an experiment made by Beaumont (1919), with certain modifications. The amounts remaining in suspension after 30 minutes' sedimentation were taken as a measure of the "degree of dispersion."

Sixty petri dishes were weighed out and 20 grams of a large well-bulked sample of air-dry clay soil added to each. These were labelled A 1-30 and B 1-30. The soil had been passed through a 3 mm. sieve, and all obvious plant remains removed.

(1) *The Series.*

Series A.

In this series it was desired to study the effect of a gradual loss of moisture. Accordingly 5 c.c. of distilled water were added to the soil in each of the 30 petri dishes by means of a burette, previous trials having shown that this quantity could be added evenly drop by drop so as to cover the whole surface, without at the same time causing any appreciable puddling. The petris were then placed in glass desiccators which, however, contained water instead of calcium chloride, where they were allowed to remain for 3 days. It was thought that this would be sufficient for the establishment of equilibrium.

On the first day of the experiment they were transferred to desiccators containing fused calcium chloride, and so allowed to lose moisture.

Series B.

These were kept for three days over calcium chloride to avoid the absorption of water from the air, wet weather prevailing at the time. On the first day of the experiment filter papers were placed in the lids, and moistened with distilled water. The soil was watered three times daily by means of a scent-spray provided with a metal bellows. One stroke of the bellows was given to each petri each time, the position of the jet being fixed relatively to the petri on each occasion throughout the experiment. The petris were kept in "desiccators" containing water.

(2) *Daily Routine.*

Treatment I. "Odd numbers." Shaken. A petri from each series was taken and weighed, after discarding the filter paper and wiping off any moisture from the lid by means of a clean dry cloth. The contents were then transferred to a Winchester containing 2 litres of the shake medium used in the bacteriological experiments, *i.e.* 0.2 per cent. sodium chloride and 0.05 per cent. sodium carbonate. No gelatine was added. Care was taken not to break up the soil crumbs any more than could be avoided. The bottles, after labelling, were tightly stoppered and placed in an end-over-end shaking machine for 30 minutes, then brought back to the laboratory, inverted two or three times, and allowed to stand for 30 minutes. During this period pipettes of 50 c.c. capacity were fitted with tightly fitting corks which were adjusted so that when the cork rested on the neck of the bottle the tip of the pipette was just in contact with the surface of the liquid. The pipette was then removed and the distance of the lower surface of the cork from the tip of the pipette measured with a ruler. The cork was then moved along the pipette till the distance had been increased by 5 cm.¹ At the end of the 30 minutes' sedimentation the pipettes were carefully replaced in the bottles so that the corks rested on the necks as before. A pipette full of the liquid was withdrawn, care being taken to avoid muddying, the level adjusted, and 50 c.c. transferred to a clean, dry, weighed, and numbered evaporating basin. Five samples were taken in this way. The basins were then placed on the steam bath and evaporated to dryness and then dried over-night in a steam oven. The following morning after cooling in a desiccator they were weighed. The weight of the dry sediment less the weight of salts present in 50 c.c. of shake medium (*i.e.* 0.125 gm.) was assumed to be a measure of the degree of dispersion attained by the shaking.

Treatment II. "Even numbers." Vibrated. One of the even numbered petris of each series was taken daily, and after weighing, the contents of each transferred to a labelled beaker. About 200 c.c. of shake medium were added and the mixture thoroughly triturated with a rubber pestle, as in an ordinary mechanical analysis. (This was omitted on the first two days, but then adopted as it was found that the vibrator had failed to break up some of the soil crumbs.) Some of the turbid liquid was poured into the vibrator vessel, the vibrator connected, and the residue of the shake medium allowed to siphon slowly in, the turbid liquid overflowing into a second Winchester, as in the bacteriological experiment. The

¹ A modification of the technique adopted by G. W. Robinson in his rapid method for mechanical analysis. *This Journal*, **12**, No. 3, 306.

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remainder of the turbid liquid in the beaker was added to the vibrator vessel from time to time as the liquid in the vibrator vessel showed signs of clearing. The beaker was finally washed out with a little of the shake medium so that all the soil was finally transferred to the vibrator vessel. After the 2 litres of shake medium had siphoned over, the two Winchesters were interchanged, the turbid liquid siphoning into the vibrator and overflowing as before. This operation was repeated. The Winchester of turbid liquid was shaken towards the end of each passage so as to bring into suspension any soil that had settled. The liquid in the vibrator vessel was stirred with a glass rod from time to time. On the conclusion of these operations, the liquid remaining in the vibrator vessel was poured into the Winchester and the residue examined. A few crumbs of soil were found on the first 2 days, but thereafter the residue consisted of clean white sand.

Table IX. *Series A. Treatment I. Shaken.*

No.	Weight of sediments in mg.					Mean	S.D.	Moisture in gm.
1	107	110	109	115	90	106	8.5	+ 4.94
3	170	156	159	172	—	164	6.9	+ 5.60
5	163	153	(257)	131	125	143	15.6	+ 4.49
7	112	113	107	117	116	113	3.5	+ 5.19
9	115	126	102	119	93	111	11.9	+ 3.58
11	122	128	105	101	101	111	11.4	+ 2.49
13	117	68	114	112	89	100	18.8	+ 2.64
15	194	193	184	182	150	181	16.0	+ 1.41
17	184	182	179	151	166	172	12.4	+ 2.79
19	224	218	214	211	201	214	7.7	+ 0.83
21	220	215	204	194	192	205	11.1	+ 0.35

Mean S.D. in each set = 11.3.

Mean of means = 147.

S.D. of means = 40.09 or 27 per cent.

Table X. *Series A. Treatment II. Vibrated.*

No.	Weight of sediments in mg.					Mean	S.D.	Moisture in gm.
2	139	160	158	147	172	155	11.3	+ 6.11
4	176	163	185	161	207	178	16.6	+ 4.90
6	170	175	192	210	186	187	14.9	+ 4.63
8	181	174	154	148	148	161	13.8	+ 4.61
10	176	190	175	187	180	182	6.0	+ 4.28
12	222	202	198	197	189	202	11.1	+ 3.82
14	171	183	178	173	189	179	6.6	+ 2.57
16	224	220	220	212	208	217	5.9	+ 2.30
18	235	225	243	207	231	228	12.1	+ 1.54
20	188	199	208	219	220	207	12.2	+ 1.09
22	196	215	217	196	210	207	9.1	+ 0.79

Mean S.D. in each set = 10.9.

Mean of last 9 means = 197.

S.D. of last 9 means = 19.8 or 10 per cent.

Table XI. *Series B. Treatment I. Shaken.*

No.	Weight of sediments in mg.					Mean	S.D.	Moisture in gm.
1	60	66	58	59	(129)	61	6.5	-0.24
3	127	96	95	84	91	99	14.8	+1.43
5	142	133	125	120	104	125	12.8	+2.81
7	135	127	109	111	105	117	11.6	+4.69
9	135	122	115	123	120	123	6.6	+4.31
11	111	135	145	138	130	132	11.5	+5.21
13	114	102	101	90	89	99	9.2	+5.47
15	164	157	154	166	160	160	4.4	+6.08
17	170	166	170	155	172	167	6.1	+6.12
19	272	218	(88)	208	206	226	26.9	+7.18
21	218	217	209	201	189	207	10.8	+8.11

Mean S.D. in each set = 11.0.

Mean of means = 138.

S.D. of means = 45.89 or 33 per cent.

Table XII. *Series B. Treatment II. Vibrated.*

No.	Weight of sediments in mg.					Mean	S.D.	Moisture in gm.
2	136	131	150	125	118	132	10.8	-0.20
4	157	138	153	166	164	156	10.0	+1.60
6	191	198	212	238	—	210	16.1	+2.99
8	196	182	169	172	175	179	9.6	+3.65
10	162	162	155	166	154	160	4.6	+4.42
12	210	196	186	182	(354)	193	9.7	+5.28
14	201	193	190	182	173	188	9.6	+5.44
16	227	221	219	215	199	216	9.4	+5.78
18	198	184	206	198	188	195	7.9	+6.08
20	226	226	212	203	216	217	8.8	+6.94
22	193	212	191	183	189	194	9.8	+8.43

Mean S.D. in each set = 9.7.

Mean of last 9 means = 195.

S.D. of last 9 means = 17.26 or 9 per cent.

The Winchester of turbid liquid was inverted two or three times and then allowed to stand for 30 minutes. 50 c.c. samples were withdrawn and evaporated as in Treatment I. The results obtained are shown in Tables IX–XII and graphically in Figs. 8–11.

An attempt was made to determine the amount of colloidal matter remaining in suspension after centrifuging for 30 minutes by shaking 250 c.c. samples with 0.75 gram of malachite green. The sodium carbonate however was found to have acted on the dye and the results were irregular. No definite conclusion could be drawn beyond the fact that there was far more colloidal matter present in the vibrated than in the shaken lots.

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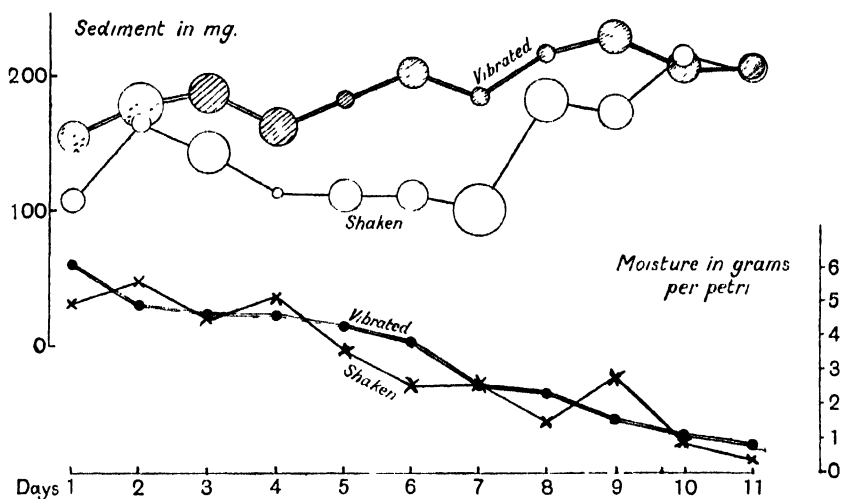


Fig. 8. Variation in weight of sediment in Series A (losing moisture)
(Radius of circle = standard deviation of set.)

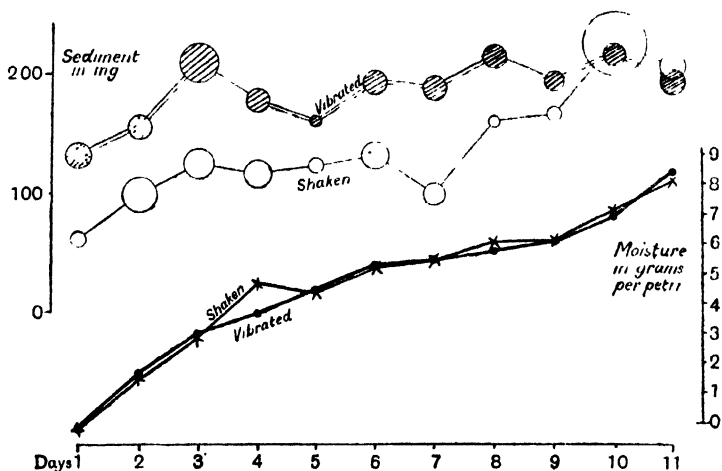


Fig. 9. Variation in weight of sediment in Series B (gaining moisture).
(Radius of circle = standard deviation of set.)

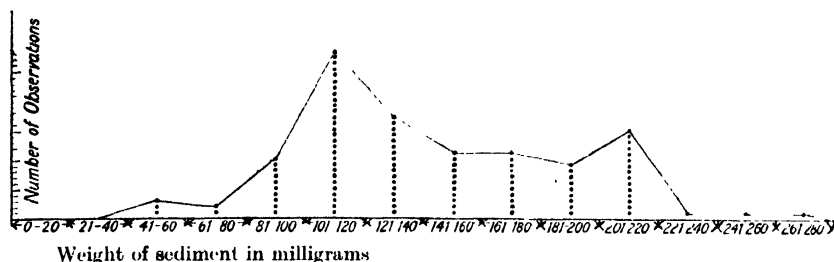


Fig. 10. Frequency distribution curve of all observations of "shaken" soils of both series.

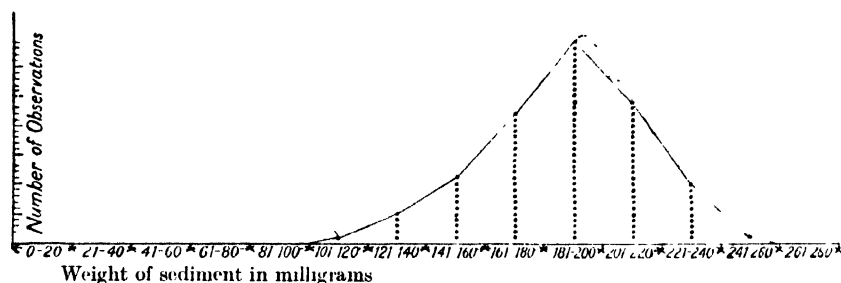


Fig. 11. Frequency distribution curve of all observations of "vibrated" soils of both series.

(3) Discussion.

From a consideration of Figs. 8 and 9 it will be seen that there is a distinct tendency for the amount remaining in suspension in the shaken series to follow the moisture curve. In Fig. 9 one observation is too low, but the reason for this could not be ascertained. Possibly this represents the optimum water content for tillage. In series A (Fig. 8) it is clear that when the soil has lost more than a certain amount of water the amount going into suspension again rises and attains a value equal to that of a saturated soil or that of the vibrated series. This at first sight appears to be rather extraordinary till one recalls how a very dry soil will spontaneously disintegrate on the addition of water. Zsigmondy's remarks on the behaviour of dry silicic acid gel are of interest in this connection.

On comparing the results of the shaken and vibrated series it will be seen that the results obtained by shaking depend on the moisture content, whereas the vibrated ones all fall more or less within the limits of experimental error. This is, however, more clearly shown by a consideration of the standard deviation of the means in each set, and of the distribution curves of the two series (Figs. 10, 11). The two peaks of the shaken lots together with the large range are strong evidence that

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these results cannot be averaged, whereas on the other hand the ideal symmetrical curve in the vibrated ones shows that these results are independent of the moisture content.

In passing it is of interest that the deviation in each set of five is very much of the same order as that usually found in parallel plate counts. In fact if they were actually counts instead of weights, they would be considered very satisfactory indeed. The comparatively large error in some of the sets was undoubtedly due to the accidental muddying of the suspension.

V. GENERAL CONCLUSIONS.

Perhaps the most striking result of the use of the vibrator was the fact that the colonies grew so quickly and attained their maximum development both in size and in numbers in such a short time as four days, whereas ten to fifteen days are required when the ordinary methods of shaking are adopted. It is suggested that this is due to the organisms having been freed from the enveloping colloidal gels in which they are normally embedded. Their metabolic products gradually accumulate in the gels, held by 'sorption, and so inhibit the growth of the colony. Dispersion of the gel involves the removal of these inhibiting substances, and so rapid growth results.

The fact that counts of the same order have been obtained by the plate method as by the direct method is fairly conclusive evidence that the low counts obtained by the usual shaking methods have little or no value. Russell (1921) claims that they "show whether the numbers are high or low and whether they are increasing or decreasing." As such counts usually range between one and several hundred millions, which is only a small fraction of the number found, it seems more likely that the variations so far recorded are rather a measure of the ease with which a soil can be dispersed than of its bacterial content.

SUMMARY.

1. The usual shaking methods have been examined and found unsatisfactory.

2. A method has been evolved for the estimation of the number of soil organisms by a direct count, and the numbers found to be very much higher than any previously reported.

3. A method for the disintegration and dispersion of the soil particles and bacteria has been devised, by means of which plate counts were made which were comparable with direct counts.

4. The dispersive actions of shaking and of vibrating have been compared. The former was found to give results which depended on the moisture content of the soil, whereas the trembling motion gave results in which the effect due to the moisture content was not apparent.

5. High counts made by previous observers can usually be correlated with one or more of the following factors:

- (i) Greater dispersion of the soil as a result of the action of frost, etc.
- (ii) An alkaline reaction, *e.g.* presence of ammonia, magnesia, etc.
- (iii) Presence of a protective colloid, *e.g.* the effect of the addition of large quantities of straw, or traces of gelatine.
- (iv) Absence of a flocculating agent, especially calcium compounds.

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THE MOISTURE EQUIVALENT OF HEAVY SOILS.

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(With one Text-figure.)

THE data on the mechanical and chemical composition of the soils of the northern Sudan¹ which has been accumulated in these laboratories for some years has recently been supplemented by several hundred determinations of the moisture equivalent, *i.e.* the percentage of moisture retained by a soil which has been drained centrifugally by a force of 1000 times that of gravity for 40 minutes. Much of the work recorded on this constant deals with the connection between it and mechanical composition, and the experiments now described aimed at extending this by seeking for relationships between moisture equivalent and such additional important soil properties as salinity and alkalinity.

The soils are, for the most part, very heavy, consisting of over 50 per cent. clay, and are usually situated under climatic conditions necessitating the use of heavy irrigation. They consequently present problems seldom met with except in tropical or sub-tropical regions.

The literature dealing with moisture equivalent is not yet very large, and the following summary gives the general results arrived at by previous workers as far as is required for the present purpose.

(a) There is a fairly consistent relationship between the moisture equivalent and many other moisture properties of soils (1).

(b) There is good correlation between the moisture equivalent and the maximum amounts of water found after irrigation (2).

(c) The hygroscopic coefficient may usually but not in all cases be calculated from the moisture equivalent (3).

(d) Whilst for a series of soils of similar nature there may be close correlation between moisture equivalent and mechanical composition, the influence on the moisture equivalent of factors other than size of particles prevents wide application of any of the formulae proposed (4 & 5).

¹ Between latitudes 10 and 20 N.

2. *Apparatus and Methods.* For the determination of the moisture equivalent the Briggs-McLane centrifuge has been used throughout, running at 2440 r.p.m. and giving a force of 1000 times that of gravity. The soil is placed in the box on a layer of filter paper, moistened with excess of water and allowed to remain in a humid chamber for 24 hours. The boxes are then centrifuged for 40 minutes, replaced in the humid chamber from which they are removed one by one and weighed. This procedure was found specially necessary in hot dry weather as the time required for weighing the 16 boxes is sufficient for the loss of about .1 gram of water.

After weighing, the boxes are placed in a drying oven at 100° – 105° for 24 hours for the moisture determination. The mechanical analyses are carried out by the sedimentation method using sodium carbonate as the deflocculating agent (6).

The uniformity of the results obtained is illustrated by those obtained for a clay soil from Wad Medani (lat. $14^{\circ} 24' N.$, long. $33^{\circ} 31' E.$): sixteen determinations of the moisture equivalent using 40 grams of soil, gave results varying from 37.13 to 38.58; the mean being 37.79 ± 0.17 .

There is some confusion in the literature relating to moisture equivalent determinations owing to the apparent lack of uniformity of procedure amongst workers with regard to detail. Both forms of Briggs and McLane's apparatus are commonly referred to, although one gives a force of 3000 gravity which is applied for 30 minutes and the other a force of 1000 gravity for 40 minutes. Again, another investigator reports results using 1000 gravity for 30 minutes: for an empirical constant of this kind, uniformity is obviously desirable. Another important variation in the method is dealt with in the next paragraph.

3. *Effect of varying the amount of soil used.* Thomas (7) has discussed the effect on the moisture equivalent of varying the amount of soil placed in the centrifuge boxes, and shows that the value decreases as increasing amounts of soil are used.

The magnitude of this alteration for some of the soils we used is shown in the following table:

Sample No.	% of clay in the soil	Moisture equivalent using		
		20 gm.	30 gm.	40 gm.
7939	72.5	53.7	51.3	49.6
6640	57.2	41.4	37.5	36.3
8940	51.2	42.8	41.9	39.2
8945	20.7	25.6	25.3	23.9

It will be seen that in each case the moisture equivalent diminishes with increasing quantity (*i.e.* thickness of layer) of soil taken, and this

is doubtless due to variations in the density of packing, which will increase in the bottom layers with increasing quantity of soil and consequently reduce the space available for water.

There is with many soils an entirely different effect which may come into play when the thickness of the layer, and consequently the density of packing, is increased. Briggs and McLane point out in their original paper (8) that when thick layers of soil are used, there is a tendency for a part of the water to accumulate on the top of the soil instead of escaping through the perforated bottom of the container. For moderate thicknesses, this will clearly only happen in the case of the more impermeable soils and will in fact indicate when an impermeable soil is being dealt with. When this is the case, the moisture equivalent will increase—and very considerably increase—instead of diminishing when the amount of soil is increased, as is illustrated by the following examples:

Sample No.	% clay in the soil	Moisture equivalent using		
		20 gm.	30 gm.	40 gm.
9320	55.6	45.1	48.5	51.6*
8939	48.8	42.0	43.2	48.1*
8889	56.1	42.1	45.0*	50.3*

The impermeability in the experiments marked with an asterisk and similar cases was shown by the accumulation of water on the top of the soil after centrifuging. It would, of course, be easy to use a quantity of soil (*e.g.* 20 grams) which would probably never allow this waterlogging¹ to be shown, but it is a valuable indication of a soil property very important in the field, particularly under irrigation, and for this reason, the amount of soil for our routine determinations has been fixed at 30 grams: this appears to be a convenient amount which will enable those soils which easily become waterlogged to be distinguished from the more penetrable ones. Although waterlogging is never observed with light soils, the proportion of clay is not the only controlling factor, and soils containing a great deal of clay and having quite high moisture equivalents often show no sign of impermeability.

4. *Factors affecting the moisture equivalent.* Reference has already been made to previous work on the relation of size of particles to moisture equivalent, the factor usually considered next in importance being the humus content. In the case of the soils here dealt with, this constituent is usually only present in small quantity, more than 0.5 per cent. of organic carbon being comparatively rare: on the other hand, as far as

¹ The term "waterlogging" is used throughout this paper to refer to the laboratory and not field observations.

soils of the same nature are concerned, the soluble salt content may be an important factor.

In the cases given below, the salt has been determined by observing the electrical conductivity of an extract made by shaking one part of air-dried soil with five parts of water and allowing the mixture to stand overnight: the approximate percentage salt content is then given by multiplying the specific conductivity of the extract by 250¹ (or by dividing 250 by the specific resistance). The measurements were made at about 30° C., but as only quite roughly approximate results were sought (and the method is not capable of refinement), temperature corrections were not used: the figures may however be regarded as comparable. The following are examples of soils of the same origin and having similar mechanical composition: the difference in their moisture equivalents may be explained by inequalities in the salt content.

Sample No.	% Clay	% Silt	% Sand	% Sol. salts	Moisture equivalent
8889	56.1	12.0	29.7	0.066	45.0
8891	57.5	16.0	24.9	0.319	42.1
8865	57.7	12.0	27.9	0.062	42.6
8867	57.2	15.1	26.2	0.262	37.3

Many similar cases have been met with: on the other hand, soils occur of the same type from closely adjacent spots or even from the same hole for which the mechanical composition and salt content are about the same but whose moisture equivalents are quite different. This is well shown by the following example:

Sample No.	% Clay	% Silt	% Sand	% Salts	Moisture equivalent
8854	47.9	12.0	35.1	.105	37.5
8926	49.6	15.2	30.3	.105	49.0

The fact that salts do in general affect the moisture equivalent is best shown by treating the same soil with different salts: work on this subject has been reported by Sharp and Waynick (9), whose practical conclusions are not easily summarised.

The experiments of which the results are given in the next table consisted of moistening the soil with a one-tenth per cent. solution of the salt instead of with distilled water, and determining the moisture equivalent in the usual way.

The difference between the effect of flocculating and deflocculating salts is clearly shown: as might be expected, waterlogging is prevented

¹ The specific resistance of a solution containing 1 per cent. of sodium chloride and sulphate is about 50 ohms at 30° C.: as a one to five soil extract is used, the constant required is 250 ohms.

when a dilute solution of a flocculating salt is used instead of water. The effect of more strongly alkaline solutions is referred to later.

Moisture equivalent when the soil is wetted with

Sample No.	Water	Ammonium sulphate	Ammonium nitrate	Calcium sulphate	Sodium carbonate
8840	38.8	36.8	38.2	35.6	40.6
8914	42.8	38.8	40.0	38.8	43.7
8841	41.8 ¹	37.8	38.3	39.6	52.0

¹ Determinations made with 20 grams, as waterlogging occurs with 30 grams.

5. *Connection between soil alkalinity and moisture equivalent.* The toxic effect of sodium carbonate on plant growth has been the subject of numerous investigations and various results have been obtained for safe limits. The subject is fully dealt with by F. S. Harris (10), but attention is apt to be concentrated rather on the immediate effect on the plant than on the more remote but equally important effect on the soil. While conclusive laboratory experiments are exceedingly hard to devise on this point, evidence has been obtained from field samples indicating that such amounts of sodium carbonate as correspond to an increase of 0.1 in the pH of a soil extract have a marked influence on soil properties. The following table refers to 10 samples of soil taken from land under cotton cultivation: the samples are all from the same area and are from the second feet, previous work having shown that the highest pH values are to be found at that level (11). The pH values were determined by means of a Leeds and Northrup potentiometer outfit using extracts of one part of soil to five of water in a Clarke's cell: the differences looked for were too small to permit of the satisfactory employment of the less accurate colorimetric methods.

Sample No.	% Clay	% Salts	Moisture equivalent	pH	Signs of waterlogging
8842	53.2	0.110	44.8	9.33	Yes
8914	52.2	0.095	51.9	9.41	Yes
8926	49.6	0.105	49.0	9.32	Yes
8938	46.6	0.078	48.0	9.46	Yes
8950	41.7	0.072	45.9	9.37	Yes
8854	47.9	0.105	37.5	9.28	No
8866	56.7	0.085	41.0	9.16	No
8878	54.2	0.133	40.9	9.29	No
8890	58.0	0.072	42.4	9.34	No
8902	57.4	0.072	46.5	9.30	No
Mean for the first five	48.7	0.092	47.9	9.38	All
Mean for the second five	54.9	0.092	41.7	9.27	None

These samples were selected because whilst they were from the same area and of the same general composition, some did and some did not exhibit waterlogging: it will be seen that those which show waterlogging have the highest pH values.

The higher pH values (corresponding to 20 per cent. more hydroxyl ions) in the plots of higher moisture equivalent suggest that alkalinity is the principal cause of waterlogging and that a small increase in pH may be of importance in this respect. It may be of interest to record that the average yield of cotton for the plots from which the first five samples were taken was 27 per cent. less than the average to which the other five belonged.

6. *Cause of high moisture equivalent.* A high proportion of "clay" seems essential for high water-retaining capacity, the factors next in importance being the amounts of humus and colloidal material: as stated above, as far as these soils are concerned, organic material is probably not of importance in this connection

The part played by colloidal material is difficult to ascertain, but some information has been obtained by determining the moisture equivalent of substances other than natural soils, for which the amount of colloidal material has been estimated by measuring the adsorption of methylene blue. Of the materials in the table below, the clays have been obtained by the usual method of deflocculation with sodium carbonate and purified by dialysis. For the moisture equivalent determinations, the suspension was allowed to dry in the air and then coarsely powdered. The methylene blue experiments were made on 1 per cent. suspensions of clay or with a weighed quantity of dry substance, equal weights of dye and material being used.

Material	Moisture equivalent	% methylene blue absorbed
Brown clay (6640) ...	57.5	34.0
Red clay (7900) ...	41.8	13.9
Slate blue clay (9228) ...	74.7	34.0
Reddish brown clay (7897) ...	51.0	23.5
Light brown clay (8378) ...	56.5	32.9
Kaolin ...	44.0	8.7 ¹
Do. ignited ...	58.0	1.9 ¹
Precipitated aluminium hydroxide	118.0	4.1 ¹
Do. ignited ...	69.4	1.4 ¹

¹ Experiments with these substances of low adsorbing power were made with five times as much material as dye.

It will be noticed that the soil clays differ considerably in the properties given: the one with low moisture equivalent has a very low dye adsorption and this agrees with the views of Comber and others (12) that

the amount of "hydrophilous surface" is governed by the amount of suspensoid colloid present. A large change in the amount of colloidal material, however, appears to be required to produce a small one in the moisture equivalent.

For the substances other than soil clays, there does not appear any such connection. The moisture equivalent of kaolin and alumina are both very high although the amount of dye adsorption, especially in the ignited substance, is small: further, ignited kaolin has actually a higher moisture equivalent than the hydrated substance.

Heat appears to destroy the colloidal matter in soils and the dye adsorption consequently is much reduced: this has recently been pointed out by Moore, Fry and Middleton in their work on ultra-clay (13). But the effect of igniting a soil is at the same time to aggregate the particles, as is shown by the examples given below:

	No. 6640		No. 9320	
	Before ignition	After ignition	Before ignition	After ignition
Moisture equivalent	37.8	11.1	48.5	13.8
Percentage clay	57.7	Nil	55.6	1.4

The reduction in moisture equivalent may therefore be as much due to the aggregation of particles as to the destruction of the colloidal material and the rôle played by the latter in determining moisture equivalent is therefore uncertain.

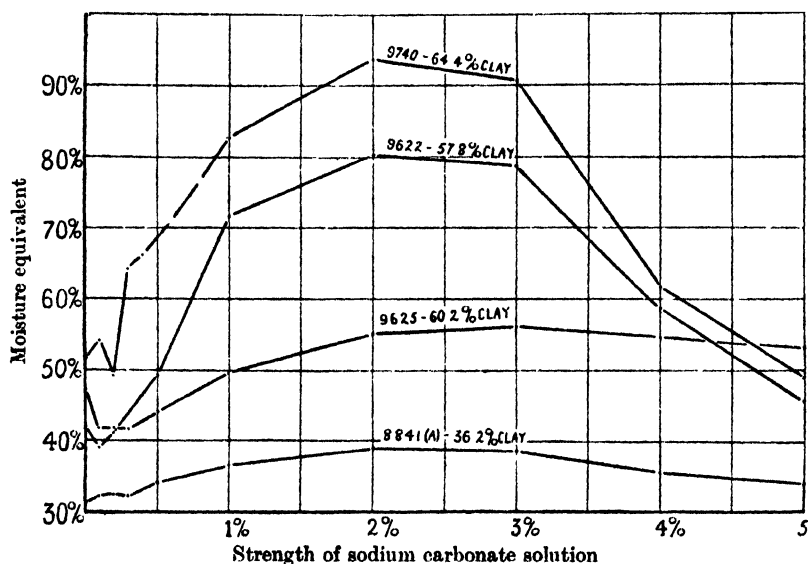
7. *Further experiments on the effect of sodium carbonate.* The results described in Sections 5 and 6 and the general importance of "black alkali" in connection with clay soils have led to experiments being made in order to investigate more fully the effect of sodium carbonate upon moisture equivalent and in conclusion the results for four soils are shown in the figure below. It will be seen that with dilute solutions, a minimum moisture equivalent is reached at a low concentration, followed by a maximum at about 2 per cent., after which it again decreases. The effect of the strong solutions are not considered further at present as such concentrations of alkali are beyond those we have met with in ordinary agricultural soils.

The concentrations for minimum moisture equivalent roughly corresponds to that at which the deflocculating effect of sodium carbonate is reversed. This has been shown by examining its effect on 0.1 per cent. purified clay suspensions, when it was found that in .3 per cent. solution the clay was completely precipitated (in a Nessler cylinder) in 3 hours, whilst it did not take place in three days when the concentration was

reduced to .2 per cent. This observation was confirmed by attempting the mechanical analysis of clay soils using sodium carbonate solution of various concentrations for deflocculation. The results were as follows:

% strength of sodium carbonate	% clay found in soil	
	No. 6518	No. 6523
0.05 ¹	58.6	59.0
0.2	59.2	58.2
0.3	29.8	31.8

¹ This is the strength ordinarily used in this laboratory. See (6).



EFFECT OF SODIUM CARBONATE ON THE MOISTURE EQUIVALENT OF SOILS.

It is clear that deflocculation ceases at a concentration between 0.2 and 0.3 per cent.

It is also of interest to note that the fluidity of clay slips treated with sodium carbonate was found by Mellor and others (14) to attain its maximum when the concentration of the alkali was 0.23 per cent. The minimum moisture equivalent is obtained with concentrations of sodium carbonate between 0.1 per cent. and 0.3 per cent., the variations being probably due to differences in the original alkalinity and total electrolyte content of the soils.

SUMMARY.

(1) The moisture equivalent of a normal soil diminishes as the weight of soil taken for the determination increases.

(2) Some soils are particularly impermeable to water in thick layers: in these cases the moisture equivalent increases with the weight of soil taken and may become very large owing to waterlogging. A soil may, however, have a very high moisture equivalent without showing waterlogging.

(3) Dilute solutions of flocculating salts such as calcium sulphate, or ammonium nitrate or sulphate, reduce the moisture equivalent, and sodium carbonate increases it.

(4) The effect of sodium carbonate is complicated: with gradually increasing concentration, the moisture equivalent first diminishes and then increases to a maximum, after which there is further diminution.

(5) The soil samples which easily showed waterlogging in the Briggs-McLane apparatus had a higher concentration of hydroxyl-ions (pH) than those which did not.

(6) Whilst the colloidal content of a clay seems related to its moisture equivalent, no such connection appears to exist for substances such as kaolin or aluminium hydroxide.

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APPENDIX ON CERTAIN EXPERIMENTAL METHODS.

As a good deal of difficulty has been experienced in elaborating satisfactory details for some of this work, the following short notes are published in the hope that they may save the time of other investigators.

1. *Preparation of clay fractions.* Enough soil to give 50 to 100 grams of clay is placed in a tubulated jar holding 10-12 litres; the tubulus carries a cork and glass tube bent upwards inside to a height of a few cms. A mark is made on the inside of the jar exactly 10 cms. above the top of this tube: this is the sedimentation column. The end of the tube outside the jar is closed with rubber and clip. The jar is filled with water to the mark and enough 10 per cent. sodium carbonate solution added to make the strength of the whole liquid .05 per cent. in order to effect deflocculation. After a period of not less than 8 hours, the top 10 cms. of suspension is run off into a vessel below, and fresh water and sodium carbonate solution added to the jar. The suspension in the vessel below is made just sufficiently acid to cause flocculation so that before the next 8 hours period is completed, all the clay will have settled and most of the supernatant liquid can be siphoned off. In this way the clay is collected all together. When this process is completed, the clay is placed in a dialyser consisting of a large (10 litre) museum jar over the top of which is tied a sheet of parchment which sags down about one-third the way inside the jar. Two tubes go through the parchment, one for siphoning off the outside liquid and the other for introducing fresh water. Each day the specific resistance of the clay suspension is determined, the dialysis being continued until it is about 30,000 ohms. The resistance of the outer liquid will show when it ought to be changed: about every two days will probably be found sufficient. Five to ten days is usually required for the dialysis. The pure suspension is then either made up to the required strength (*e.g.* 1 per cent.) by suitable dilution, or allowed to evaporate at a temperature not exceeding 40° in a large

photographic dish. For most purposes, there is no objection to concentrating the suspension on the water bath before finishing at a lower temperature.

2. **Measurement of the methylene blue adsorption.* 0.1 gram of dried clay or 10 c.c. of 1 per cent. suspension is put into an ordinary soil centrifuge tube (with 10 c.c. of water in the former case) and to it is added 20 cc. of methylene blue solution prepared by dissolving 5 grams of the dye in a litre of 10 per cent. alcohol. 45 c.c. of water are next added, the tube shaken and 5 c.c. of normal sodium chloride added. The tube is then centrifuged for 5–10 minutes, a portion diluted 10 times and matched in a Dubosq colorimeter against the original methylene blue solution, also suitably diluted. The result is expressed as the number of centigrams of dye adsorbed by 1 gram of the substance.

The weight taken may be increased in the case of substances whose adsorbing power is low, but results are not strictly comparable with the others. For the purposes of this paper, however, this is not of importance.

(Received August 1st, 1922.)

ON THE ESTIMATION OF NITRATES IN SOILS BY THE PHENOL DISULPHONIC ACID METHOD.

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So many papers on the use of the phenol disulphonic acid method for estimating nitrates in soils have been published in this country and in America in the last few years, that some apology seems needed for adding yet another note to the literature of the subject. The method possesses great advantages as regards rapidity and convenience over the methods involving distillation and yet in the writers' experience, in spite of the numerous studies already made, it has failed to give entirely satisfactory results; in particular when small quantities of nitrate have to be estimated in soils containing much organic matter, the strong sulphuric acid in the reagent chars the organic matter and makes it exceedingly difficult to match exactly the tints from the soil extracts with those given by the standard nitrate solutions.

It is therefore perhaps not inopportune to draw special attention to a recent paper by Emerson¹, and at the same time to sound a note of warning in regard to one practical point.

The new part of Emerson's method lies in the preparation of the soil extract before evaporation and addition of the phenol disulphonic acid reagent. He uses very thoroughly washed aluminium hydroxide (prepared by precipitation with ammonia from potash or ammonia alum) to clarify and decolorize the original extracts, then filters and washes to a known volume and estimates nitrates in the usual manner in the filtrate.

On trying this method, Emerson's results as regards the efficiency of aluminium hydroxide for this purpose were at once confirmed and very satisfactory colours were obtained; but, working with solutions containing known very small amounts of nitrate, the figures were almost always found to be too low and were very irregular. By eliminating the possible sources of error one by one the difficulty was finally traced, not to the aluminium hydroxide, but to the particular kind of filter paper in use, which retained sufficient nitrate from these very dilute solutions to

¹ *Soil Science*, 12, No. 5, p. 413.

affect the results seriously. Nitrate taken up in this way was exceedingly difficult to recover even by prolonged washing. On substituting a different and coarser paper very good figures were obtained and the method has continued to give very satisfactory results.

As an example, in one set of comparisons with a standard solution containing sodium nitrate equivalent to four parts nitrogen per million, the following tests were made with three grades of filter paper:

(a) 40 c.c. standard solution filtered; filter paper washed up to 100 c.c.; 25 c.c. filtrate (equivalent to 10 c.c. standard) taken for determination.

(b) 20 c.c. standard solution filtered; filter paper washed up to 100 c.c.; 25 c.c. filtrate (equivalent to 5 c.c. standard) taken for determination.

The results were compared with standard colours obtained by

(1) Diluting 40 c.c. standard solution to 100 c.c. and taking 25 c.c. (equivalent to 10 c.c. original solution);

(2) Taking 10 c.c. undiluted standard solution;

(3) Diluting 20 c.c. standard solution to 100 c.c. and taking 25 c.c. (equivalent to 5 c.c. original solution);

(4) Taking 5 c.c. undiluted standard solution.

Standards (1) and (2) agreed very satisfactorily, as also did Standards (3) and (4).

Blanks were made by passing distilled water through each of the papers used up to 100 c.c. and taking 25 c.c. for a nitrate determination. These gave perfectly colourless solutions in every case.

Tests (a) and (b) were repeated, with the addition in each case of calcium carbonate and aluminium hydroxide to the solution before filtration, according to Emerson's method. The results of the determinations expressed as percentages of the amount of nitrate actually present were as follows:

	Filtration of standard solutions without any addition		Filtration of standard solutions with previous additions of CaCO_3 and Al(OH)_3	
	(a)	(b)	(a)	(b)
Filter paper I	72	68	78	80
" " II	100	68	78	84
" " III	100	98	100	96

Filtration through filter paper III caused no serious loss of nitrate, even with the very dilute solution (b); whilst the other two papers retained a considerable percentage of the nitrate present, which was not removed by further washing.

62 *Nitrates in Soils by Phenol Disulphonic Acid Method*

With a suitable filter paper such as No. III it is not necessary to use a large volume of water for washing the aluminium hydroxide—20 c.c. of original extract (or even 40 c.c.) treated with the hydroxide, filtered and the washings made up to 100 c.c. yields all the nitrate originally present in the filtrate, if the washing is done carefully. The filter paper III is Whatman No. 1¹, while unsatisfactory results were obtained with Whatman No. 40 and Green, Grade 2^{JG}.

It is recognised that the retention of some nitrate from very dilute solutions by filter paper may affect other methods also, for the soil extract has to be filtered at least once whatever method is used. It seems not unlikely that some of the difficulties met with in getting concordant results by any of the usual methods where small quantities of nitrates in soil have to be determined may be due to this cause.

It may be convenient to add details of the method.

100 gms. soil, together with a little precipitated calcium carbonate as a flocculant, are thoroughly shaken with 400 c.c. distilled water for 15 minutes, and then allowed to settle until the supernatant liquid is fairly clear. (The writers have used smaller quantities of soil and water in the same proportion.) An aliquot is then taken with a pipette, a suitable quantity of the moist aluminium hydroxide added, the liquid stirred and filtered through a suitable coarse filter paper. The hydroxide is carefully washed, the filtrate and washings collected in a measuring flask and made up to a known volume. Nitrates are then determined in the clear and colourless filtrate with phenol disulphonic acid by the usual procedure.

The weight of soil and the size of the aliquots to be taken can be regulated, as convenient, by the approximate quantity of nitrate present; and the amount of aluminium hydroxide required to decolorize the soil extract may be judged by preliminary trials or, if necessary, can be ascertained by comparison with a series of standard colours made by dilutions of a 1 per cent. caramel solution. "Weak solutions of caramel give colour concentrations very similar to those of soil extracts and equivalent amounts of aluminium hydroxide decolorize either." Decolorization is almost immediate and the method is rapid.

¹ Emerson recommends a "coarse" filter paper but does not draw special attention to this point.

ESTIMATION OF NITRIC NITROGEN AND TOTAL NITROGEN IN PLANT TISSUE EXTRACTS.

By PATRICK HUGH GALLAGHER, M.Sc.

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(With one Text-Figure.)

IN the course of an investigation of the simpler or non-protein nitrogenous constituents of some of the more common vegetable roots, particularly the mangold-wurzel, it was found necessary to carry out the following critical survey of methods of nitrate reduction from the point of view of the more simple and accurate estimation of nitrate nitrogen. In the course of some total nitrogen estimations which were carried out in the month of January on the juice of the mangold, the salicylic acid-zinc dust method of Jodlbauer¹, of which use was made for the reduction of nitrates, was found to give rather unsatisfactory results. In the first place, owing to the volatility of salicylic acid with steam, the method cannot be satisfactorily applied to the analysis of plant extracts until these have been first evaporated nearly to dryness. Secondly, at the period at which it is necessary to add the zinc dust, we have frequently to deal with a liquid in a frothy and viscous condition. Under these circumstances quantitative reduction is rendered difficult. While these conditions impair somewhat the general efficiency of the method, it must at the same time be remembered that it is inapplicable to the separate estimation of nitrates in presence of nitrogen in other forms.

Various other methods of nitrate reduction were examined in consequence, among which were the following: (a) with aluminium amalgam, (b) with zinc-copper couple, (c) Devarda's method, and (d) Ulsch's method.

The aluminium amalgam method.

The use of aluminium amalgam has been recommended by Pozzi-Escot². In his estimations he added sodium hypophosphite towards the end of the ammonia distillation to decompose possible mercur-ammonium compounds. This method has since, however, been rather

¹ *Chem. Centr.* iii, xxii, 433.

² *Compt. Rend.* 1909, **149**, 1380.

adversely criticised. Theoretically the aluminium amalgam method would appear to have certain advantages, notably in that the reduction takes place readily at room temperature and in neutral solution. The possibility of decomposition of organic nitrogenous substances by acids or alkalis would thus be avoided. This method was accordingly submitted to special examination. Analyses were carried out on a solution of sodium nitrate containing 10.0 gm. of NaNO_3 per litre. The yield of ammonia, however, was considerably below 80 per cent. In subsequent trials the amalgam was carefully prepared before being added to the nitrate solution. The aluminium foil was first immersed in 40 per cent. caustic soda and then washed with plenty of distilled water before placing it for three minutes in 0.5 per cent. mercuric chloride solution. It was finally washed again with distilled water to free it from mercury salts. Sodium hypophosphite and sodium sulphite were each used towards the end of the distillation to decompose possible mercur-ammonium compounds. In no case, however, was a higher yield than 80 per cent. of the theoretical obtained.

It is to be noted that after reduction with aluminium amalgam, the residue gave no nitrate coloration with diphenylamine and concentrated sulphuric acid. A probable explanation of the deficiency of ammonia is that some of the nitrogen is lost during the reduction either in the free state or as oxide.

Zinc-copper couple was inconveniently slow in its reducing action, but with Devarda's and Ulsch's methods accurate results were readily obtained with standard nitrate solution.

*Error involved in reducing nitrates in acid medium
in presence of amino acids.*

In the estimation of nitrates by means of an acid reducing agent a serious objection exists when amino groups, whether in the form of amino acids, or of protein, etc., be present. The first step in the reduction of nitrates would appear to be the formation of nitrites. In presence of acid, nitrous acid is thus formed, which, of course, will quickly react with the amino groups of amino acids, etc., with liberation of nitrogen. While Ulsch's method, involving the use of hydrochloric acid and reduced iron, gave quite accurate results with a solution containing nitrate only, a solution containing 14.84 mg. of nitrate nitrogen and 9.13 mg. of nitrogen in the form of asparagine, on reduction by this method and subsequent completion of the Kjeldahl digestion, gave a total of 13.70 c.c. $N/10$ ammonia instead of 17.10 c.c. $N/10$ (being a loss of nearly 20 per cent). The evident remedy would appear to be to use an

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ERRATUM

p. 64 line 14 for Sodium Sulphite *read* Sodium Sulphide

alkaline reducing agent and thus avoid the formation of free nitrous acid.

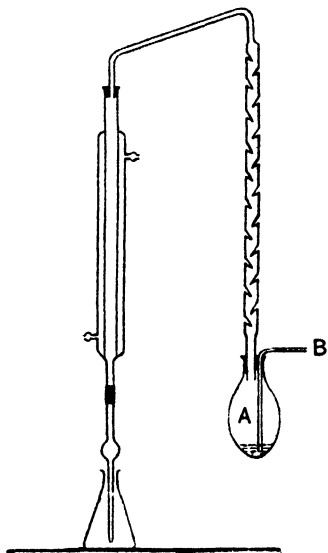
In consequence of these considerations, Devarda's method, involving the use of Devarda's alloy and of sodium hydroxide, was selected for more thorough examination in preference to that recommended by Ulsch.

Devarda¹ recommends, for reduction of $\frac{1}{2}$ gm. of potassium nitrate dissolved in 60 c.c. of water, the use of 40 c.c. of potassium hydroxide solution of specific gravity 1.3, together with 2-2 $\frac{1}{2}$ gm. of alloy of aluminium (45 per cent.), copper (50 per cent.), and zinc (5 per cent.). The use of strong potash solution, as mentioned, renders the separate estimation of nitrates in such media as plant extracts practically impossible. On substituting freshly ignited magnesia for the potash, however, and distilling for 45 mins. in a current of steam, very satisfactory results were obtained.

An apparatus specially adapted to the purpose of this estimation is that shown in the figure. The flask *A* is of about 300 c.c. capacity. It contains the solution to be analysed together with the requisite quantity of magnesia and of Devarda's alloy. It is connected with an air condenser of the Vigreux pattern, as shown. The purpose of inserting a reflux condenser of this type was to regulate the condensation of surplus steam so that the standard acid in the receiver was not unduly diluted. A reflux tube of 25-30 cms. was found to be quite efficient for this purpose. The tube *B* through which the steam enters the apparatus should reach nearly to the bottom of the flask. A fairly brisk current of steam is advisable, particularly during the early part of the distillation, in order to insure thorough agitation of the alloy. The alloy itself should be in a very fine condition. It ought to be sufficiently fine to pass through a sieve of 0.2 mm. meshes before weighing it out for the estimation.

10 c.c. of a solution of sodium nitrate containing 10 gm. of NaNO_3 per litre were thus treated with 1 gm. of Devarda's alloy and $\frac{1}{2}$ gm. of freshly ignited magnesia and distilled in steam for 45 mins. The distillate collected in *N*/10 acid contained 11.8 c.c. *N*/10 ammonia.

¹ *Chemiker Zeitung*, 1892, 16, 1952.



That required by theory = 11.76 c.c. $N/10$. A blank determination with the same apparatus, in which distilled water and the same quantity of magnesia were used, gave 0.1 c.c. $N/10$ ammonia.

In the estimation of nitrates in plant juices or tissue extracts a certain quantity of ammonia is invariably produced by the action of the magnesia alone on other nitrogenous substances present. A blank estimation in all cases, in which an equal quantity of solution is distilled with a similar amount of magnesia during the same period as when the reduction was being carried out, is thus rendered essential. The quantity of ammonia thus obtained is quite considerable in some cases, but we have invariably found duplicates to be in excellent agreement. In dealing with solutions containing much colloidal or protein matter it will generally be found advisable to precipitate and remove such before the estimation. For this purpose the addition of an equal volume of rectified spirit and subsequent filtration will be found quite satisfactory. If a higher proportion of alcohol be used (as was the case in some of our earlier estimations) the end-point with methyl orange may be rendered obscure. In such a case alizarin-red as recommended by Foreman¹ may be substituted.

Experiments carried out on mixtures of plant extracts and standard nitrate solution for the purpose of testing the accuracy of the method have given satisfactory results. Thus the juice of a mangold of the "yellow globe" variety, taken from the storage pits on January 24th, was treated with nine volumes of rectified spirit (see previous observation on addition of spirit) and filtered after standing overnight. 50 c.c. of the filtrate were then distilled with 1 gm. of Devarda's alloy and $\frac{1}{2}$ gm. of freshly ignited magnesia for $\frac{3}{4}$ hour. Amount of ammonia obtained = 4.95 c.c. $N/10$. A corresponding blank determination in which 50 c.c. of the alcoholic solution were distilled with steam for the same length of time with $\frac{1}{2}$ gm. of magnesia gave 1.2 c.c. $N/10$ ammonia. The amount of nitrate nitrogen in 1 c.c. of juice is thus 1.05 mg.

50 c.c. of the same alcoholic solution were then added to 2 c.c. of a solution of sodium nitrate containing 1 per cent. of NaNO_3 and the estimation was repeated. 7.25 c.c. $N/10$ ammonia were thus obtained on reduction and distillation. Steam distillation of the mixture with $\frac{1}{2}$ gm. of magnesia alone gave 1.2 c.c. $N/10$ ammonia.

Hence amount of nitrate in mixture = 6.05 c.c. $N/10$.

That required by theory = 6.1 c.c. $N/10$.

Asparagin, a compound of wide distribution in plants, is known to

¹ *Biochemical Journal*, 1920, 14, 451.

be readily reduced to ammonium succinate by bacterial action. Were such a reaction to take place through the action of the reducing agent used for the purpose of nitrate reduction a serious source of error would arise. Experiments carried out on solutions of asparagin indicate, however, that no ammonia is produced by the action of Devarda's alloy and magnesia other than that arising from the action of magnesia alone.

Reduction of nitrates in the estimation of total nitrogen by the Kjeldahl method.

In the estimation of the total nitrogen of substances containing nitrates it is essential, if even reasonably approximate results are to be expected, that care be taken to reduce the nitrates completely before digestion with sulphuric acid. Paul and Berry¹ give some interesting observations of the effect of nitrates and of nitrous fumes on total nitrogen estimations by the Kjeldahl method under different conditions. Their results indicate the importance of first reducing nitrates to ammonia whenever their presence is suspected. In actual practice, the residue from a nitrate estimation may be conveniently used for the Kjeldahl process, thus effecting an economy of the product under examination. But if one's chief aim is the total nitrogen determination, the reduction may be carried out by the addition of 1 gm. of Devarda's alloy and 2 c.c. of 25 per cent. NaOH to 10-25 c.c. of plant extract. The mixture is then distilled directly for 30 mins. The ammonia thus obtained is added to that finally found in the Kjeldahl distillation. The advantage of soda over magnesia in this particular instance lies in the fact that if the latter be used a tendency to "bumping" is noticed during the subsequent digestion with acid. Nitrate reductions are invariably essential in dealing with Kjeldahl estimations of plant products, since the plant contains nitrates at nearly all stages of growth.

The use of Devarda's alloy as thus described has given satisfactory results. Since the completion of the work on nitrates just detailed we have found a reference to a paper by Allen². He recommends reduction by the use of Devarda's alloy and *N*/10 NaOH solution. The use of magnesia, he says, leads to unsatisfactory results in presence of organic matter. Such, however, has not been evident in our experience. Both in the case of the reductions and in the blank determinations, duplicates have been found in excellent agreement. The advantages of magnesia

¹ *Association of Official Agricultural Chemists*, 1921, **5**, 130.

² *J. Ind. Eng. Chem.* 1915, **7**, 521.

in our view lie, not alone in its lesser activity as an alkali, but also in the fact that its relative insolubility enables it to maintain a faint and definite alkalinity throughout the whole distillation, thereby giving better comparison between the actual estimation and the blank determination.

SUMMARY.

Several methods for estimating nitrates by reduction to ammonia were examined. The error involved in the use of acid reducing agents in presence of amino groups was emphasised.

A method based on the use of Devarda's alloy and magnesia is recommended.

In the estimation of nitrates in plant extracts, etc., by this method an equal volume of rectified spirit is first added to the solution to precipitate colloidal matter. The precipitate is filtered off and an aliquot part of the filtrate containing the equivalent in nitrate nitrogen of about 0.1 gm. of KNO_3 is distilled with steam for 45 minutes with 1 gm. of Devarda's alloy and $\frac{1}{2}$ gm. of freshly ignited magnesia. A blank determination is essential, in which the same volume of filtrate is distilled for the same length of time with $\frac{1}{2}$ gm. of magnesia.

In Kjeldahl estimations in presence of nitrates, where the separate estimation of nitrates is not required, 2 c.c. of 25 per cent. NaOH may be substituted for the magnesia. Relatively this is very much less soda than Devarda recommends. The mixture in this case may be distilled directly for half-an-hour. The nitrates are thus reduced and the ammonia produced is collected before beginning the digestion with sulphuric acid.

This work was carried out under the supervision of Mr F. W. Foreman to whom the author's best thanks are due for much valuable criticism and advice.

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ON THE COLORIMETRIC DETERMINATION OF HYDROGEN-ION CONCENTRATION IN SOILS.

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OF the two available methods for the determination of hydrogen-ion concentration, the electrometric is the more fundamental and satisfactory but it requires somewhat elaborate and expensive apparatus. The colorimetric method, on the other hand, though not lacking in difficulties if accurate results are wanted, requires no special apparatus and the actual procedure is simple. It is based on the electrometric method, and involves the use of buffer solutions of known hydrogen-ion concentration determined originally electrometrically.

Insufficient study has yet been given to the correlation of the two methods in their application to soils; but the evidence so far available seems to justify further work on the colorimetric method, whilst waiting for the results of the more fundamental comparison of the two methods which is being carried out at Rothamsted¹.

In making use of the colorimetric determination of hydrogen-ion concentration, the writer has followed for the most part the details given by E. A. Fisher⁽¹⁾; and as these are set out fully and clearly in his paper, it is not necessary to do more than refer to them briefly.

A water extract of the soil is prepared with "conductivity" water, and after allowing to stand a few minutes the supernatant liquid is centrifuged and the determinations made on the centrifugate. The hydrogen-ion concentration (more conveniently expressed as the P_H value, i.e. the reciprocal of the logarithm of the hydrogen-ion concentration) is arrived at by comparing the colour given by the soil extract on addition of a suitable indicator with the colours given with the same indicator by a series of standard buffer solutions of known P_H value. The comparison of the colours is made in small test-tubes in a specially constructed rack, which, as suggested by Fisher, is a modified form of Walpole's tintometer.

Soil extracts prepared in this manner are always turbid and often

¹ For a valuable résumé of studies on soil reaction see E. A. Fisher, *Journ. Agric. Sci.* **11**, 19.

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brownish or yellowish in colour, but the arrangement just referred to makes it possible to compare the colours of liquids of considerable turbidity and natural colour, the disturbance due to these being compensated for. It is however none the less true that the greater the turbidity of the liquid, the less satisfactory is the determination.

The interference due to suspended matter in the soil extract seems to be the greatest difficulty in the satisfactory application of the colorimetric method to soil work. Not only does it introduce great difficulties in the visual comparison of the colours, but what is even more serious, the minute suspended particles appear to absorb the colouring matter or at all events alter the intensity of the colour of certain indicators in general use, thus leading to unreliable results.

A number of flocculants has been tried for coagulation of the suspension but none has yet been shown to be satisfactory¹. Nor can filtration, either through paper or a Pasteur-Chamberland candle, be used since both these procedures may affect the P_H value of the extract; while reduction of the turbidity by dilution with "conductivity" water, which has been recommended, has, in the writer's experience, given rise to irregularity and error.

In the present paper, a short account is given of the results so far obtained in an attempt to get over the difficulties due to turbidity by utilising a *displacement* or *percolation* method.

Downward displacement by a liquid was originally suggested as long ago as 1866 by Schloesing⁽²⁾ as a means for obtaining the actual soil solution for the study of its concentration and composition. It was further studied by Gola⁽³⁾ and by Ischerekov⁽⁴⁾ and recently by F. W. Parker⁽⁵⁾.

The displacing liquid, whether alcohol or oil or water, is poured on the top of a column of soil in a cylinder and "as it penetrates the soil it displaces some of the soil solution which forms a zone of saturation below the displacing liquid... When the saturated zone reaches the bottom of the soil column, the soil solution, free from displacing liquid, drops from the soil"⁽⁵⁾. It seemed possible that the soil solution or concentrated soil extract (referred to here as the percolate) obtainable in this way might be utilised for the determination of P_H values.

In most of the experiments on this method, plain glass cylinders have been used for the percolations, 12" long and 2" diam., fitted with a waxed

¹ Gillespie (*Soil Sci.* 9, 115) tried colloidal ferric hydroxide and succeeded in obtaining perfectly clear soil extracts, which gave P_H values colorimetrically, agreeing well with those given by the usual centrifuged extracts. The experiments were however carried out with a few soils only and the author does not recommend the method without further investigation.

cork at the bottom end into which is inserted a short tube of about $\frac{1}{2}$ " diam., drawn out at the lower end. A layer of coarse sand, thoroughly cleaned, is placed in the tube at the bottom and the soil in a suitable condition as regards moisture is packed into the cylinder to a depth of 8"-10" and is then percolated with twice-distilled water. Alcohol was employed at first, but water has proved more satisfactory, particularly as the object was not, as in Parker's experiments, to obtain the undiluted soil solution, but merely a clear soil extract. The packing of the soil in the cylinder is the only matter that presents any difficulty—too tight or too loose packing must be avoided. With a little practice however it is easy to judge the most suitable proportion of moisture to have in the soil and the amount of ramming required to give a column of soil through which the water will percolate evenly and in a reasonable time. When possible, air-drying the samples of soils has been avoided, and they have been brought to a suitable moisture content by partial drying or the addition of twice-distilled water, according to the condition in the field at the time of sampling. The packing of very heavy soils requires special care.

The volume of percolate which runs through almost clear varies with the moisture content and the packing, but given suitable packing, at least the first 50 c.c. and often the first 100 c.c. or more are either perfectly clear or with a slight opalescence. Later portions of the percolate from most of the soils tested became turbid. There is no difficulty in matching the colours of the buffer solutions with the colour given on the addition of the indicator to the soil extract or percolate obtained in this way. Any natural colour, as distinct from turbidity, is compensated for without difficulty.

Since the buffer action of soils is apparently due entirely to some part of the solid matter present, such comparatively clear percolates are much less highly buffered than a more turbid extract, and the hydrogen-ion concentration is more sensitive to change due to small quantities of alkali or acid from the glass or the air with which they are in contact. It is therefore best to determine the P_H value as soon as sufficient liquid is obtained; and, when necessary, to protect it from the laboratory atmosphere.

By taking these precautions, very consistent P_H figures for samples of the same soil taken at different times and under different moisture conditions have been obtained.

Further, through the kindness of Mr E. M. Crowther of Rothamsted it has been possible to make some comparisons between P_H figures

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obtained colorimetrically on the percolate and figures obtained electrometrically on samples of the same soil, and in many cases there is a good agreement between the two sets of figures.

Table I gives some of the comparisons.

Table I.

Soil	Electrometric (E. M. Crowther)		Colorimetric (using percolate)	
A	4.71	4.64	4.6 to 4.8	Determined on many different samples
B	5.09	5.12	4.7 " 5.1	" " "
C	5.52	5.66	5.5 " 5.6	" " "
D	6.66	6.73	6.7	" " "

In all these cases agreement is good.

On the other hand some figures obtained later in the course of the work with other soils seem to suggest an effect on the hydrogen-ion concentration due to turbidity, *i.e.* to the solid particles present, which is not compensated for by using the tintometer.

For example, a soil for which the electrometric figure is 6.05 gave a value of only 5.2 colorimetrically on the first 50 c.c. of percolate which ran through quite clear; on collecting a second 50 c.c. which was slightly opalescent, the value was found to have risen to 5.85; whilst a third and fourth 50 c.c. which were distinctly turbid gave a value of 6.0, agreeing with the colorimetric figure. Later runnings were too turbid for satisfactory colour matching. These figures are given in Table II, together with other examples. The electrometric figure however is available for comparison only in two cases.

Table II.

Colorimetric Determinations on Successive Fractions of Percolate. (Brom-cresol-purple as indicator.)

Soil A				P _H value		Soil B				P _H value	
1st 50 c.c. (clear)	...	...	...	5.2		1st 50 c.c. (clear)	...	...	...	6.3	
2nd "	(opalescent)	...	...	5.85		2nd "	(slightly opalescent)	...	...	6.5	
3rd "	(turbid)	...	...	6.0		3rd "	(turbid)	...	...	6.7	
4th "	(more turbid)	...	...	6.0		4th "	(more turbid)	...	...	6.7	
Electrometric figure	...	...	...	6.05		Electrometric figure	...	...	...	6.61	
Soil C						Soil D					
1st and 2nd 30 c.c. (clear)	...	...	...	5.45		1st 50 c.c. (clear)	...	...	...	6.2	
3rd 30 c.c.	increasingly opalescent but never really turbid			5.65		2nd "	(turbid)	...	...	6.65	
4th "				5.75		3rd "	"	...	...	6.65	
5th "				5.9		4th "	"	...	...	6.65	
6th "				6.4							
Soil E						Soil F					
1st, 2nd and 3rd 50 c.c. (clear)	...	...	...	6.15-6.3		1st 50 c.c. (clear)	...	...	...	6.0	
4th and 5th 50 c.c. (turbid)	...	...	...	6.7		2nd "	(opalescent)	...	...	6.45	
						3rd "	(more opalescent)	...	...	6.7	

It has not unfortunately been possible to follow up these results but it appears evident that, at all events in certain cases, the amount of suspended matter present in the soil extract may influence the P_H value determined colorimetrically. If this were due to absorption of some of the indicator colour by the fine particles present, the P_H value determined colorimetrically, which agrees with the electrometric figure, should be that given by the clear or nearly clear percolate instead of that given by the later turbid percolate. Moreover with brom-cresol-purple as indicator, any removal of colour would tend to make the liquid appear more rather than less acid. This cannot therefore be the explanation.

Though no doubt the effect is connected with the degree to which the different portions of the percolate are buffered, it is not immediately apparent that the earlier clear portions of the percolate are changing in P_H value too rapidly for a colorimetric determination. The colour comparison is always perfectly satisfactory and clear percolates have frequently been kept for several hours and the P_H value determined at intervals without finding any appreciable change. Usually, on standing overnight or longer, the reaction has changed appreciably towards neutrality, but this has also sometimes occurred in the case of turbid liquids.

The writer regrets that the work has had to be abandoned at an early stage. Repetition of the experiments and many more comparisons both with figures obtained colorimetrically on the soil extract made in the usual way and with figures obtained electrometrically are required; but these preliminary results are placed on record with the suggestions that the percolation method is worth further trial and that it may prove useful in studying certain aspects of soil reaction, particularly those connected with the degree of buffering of soil extracts. An investigation of the nature of the buffer action of aqueous soil extracts and of the substances to which it is due is much wanted.

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SOME FACTORS AFFECTING MILK YIELD.

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(With eighteen Text-Figures.)

INTRODUCTION.

AN investigation was undertaken with the object of studying some of the factors which influence the amount of milk a cow gives in one lactation, and of ascertaining the corrections to apply for these factors when considering the cow's milk record, so as to calculate what she would probably have given under certain normal and standard conditions. If this could be done for all the environmental factors involved in affecting the yield, the genetic grade of a cow for milk production could be determined from one lactation yield.

The following factors were studied:

- (1) Month of the year in which the cow calves.
- (2) The Service Period, *i.e.* the length of the interval between calving and the next fertile service.
- (3) Age—as measured by lactations (1st, 2nd, etc.).
- (4) The Dry Period, *i.e.* the period of rest preceding the lactation under consideration.

It is not suggested that these are by any means the only factors which will influence the yield; feeding, methods of treatment, methods of milking, weather, etc., in all probability have a large effect on the total yield.

In the hope of eliminating these influences as far as possible, the investigation was restricted to one Milk Recording Society, in which the prevailing methods of feeding, and the conditions to which the cows are subjected, are only moderately variable. Furthermore it was desirable that the cows considered should all be of one breed.

Investigations were made on the variation due to the month of calving from the returns of several Milk Recording Societies situated in different parts of England, in order to determine how far variations due to this cause were dependent on local conditions.

DATA.

The Society selected for the detailed investigation of the factors involved was the Penrith (Cumberland and Westmoreland) Milk Recording Society; all the cows were Shorthorns—chiefly non-pedigree.

The registers containing the weekly weights of milk given by individual cows were obtained from the members of this Society; lactations were copied out according to the month of calving, separate sheets being used for January calvers—and so for the succeeding months. The yields during the 1st, 2nd, etc., weeks after calving were extracted and a period of over three days was reckoned as a week and corrected accordingly—the need for this correction only arising at the beginning or end of a lactation or of a milk recording year (Oct. 1st).

Lactations were rejected in which:

- (1) there was any illness;
- (2) the service period was not known;
- (3) the cow suckled her calf for more than 20 days (only in a few cases was the suckling period longer than the official four days).

With these restrictions all lactations were extracted and 1410 were obtained; in these it was known in all except eight cases whether it was the cows 1st or 2nd, etc., lactation, and in 711 cases the dry period preceding calving was ascertainable and was noted.

Some of the data for the work on the variation due to month of calving were derived from the yearly returns of Milk Recording Societies, obtained from the Ministry of Agriculture, and in this case the records were from midday, Oct. 1st of one year to the same time in the following year. From the returns of the Societies selected the records of all cows were taken over a period of 3–5 years (varying with the life of the Society), the exceptions being the same as those given above, and no yield was included in which the cow was not recorded for the full year.

I. PRELIMINARY INVESTIGATION.

The effect of the month of calving on the yield of milk a cow gives is shown in Table A (1), which has been compiled from the yearly returns of two Milk Recording Societies in the East of England and two in the West.

It will be seen that in all cases the highest yields are attained by cows calving in the autumn months, the month with which the highest yield is associated depending on local conditions. Cows calving during the successive winter and spring months show gradually decreasing yields, until about June or July, when the minimum is reached.

Table A (2) shows the percentage of cows which calve in the different months of the year in each of the four districts.

It will be seen that in the East of England calving is distributed more evenly than in the West (except N. Somerset which supplies winter milk to Bristol) where a very large percentage of the cows calve in the spring months. This, together with the fact that spring calvers yield less than autumn calvers, accounts in part for the differences in the average yield of East of England and West of England Milk Recording Societies. In the year 1917-18⁽¹⁾ the counties having the highest yields were Norfolk (6735 lbs.), Yorkshire (6687 lbs.), Bedfordshire (6679 lbs.), and Essex (6531 lbs.), and those having the lowest yields were Westmoreland (4840 lbs.), Cumberland (5744 lbs.), Nottinghamshire (5694 lbs.), and Somerset (5891 lbs.). The time of calving does not account, however, for the whole of these differences for in Table A (1) the last column gives the average yield of equal numbers of cows calving in all months (*i.e.* the above effect is eliminated) and here the Western yields are still below those of the East—although the differences have been reduced.

No doubt the arable conditions of the East, with winter provision of roots and forage crops in autumn, are responsible in part for these differences. Much depends however on the breed of cows kept in the district. In Norfolk a large number of different breeds are kept, and it was possible to compare the yields of various breeds all kept in the same district.

Table B. *Average yield (lbs.) per year of different breeds*
(Norfolk Milk Recording Society).

Breed	Average yield, lbs.	No. of lactations from which calculated
Park cattle	7108	19
Cross-breeds (Shorthorn cross)*	7064	955
Friesian	7015	199
Lincoln Red	6869	211
Red Poll	6701	354
Guernsey	5999	2
Jersey	5594	22
Shorthorn	5478	36

* And non-pedigree Shorthorns.

While in some cases the numbers of cow-years on which the results are based are very small, they indicate that the cross-bred and non-pedigree Shorthorns and Friesians are the highest yielders while the pure bred Shorthorns, owing probably to the inclusion of beef blood, figure low on the list.

While the average yield in the different counties may be affected by this factor, it does not necessarily follow that the highest average yield

is the most profitable, for the difference in size between the Friesians and Lincoln Reds as compared with the Red Poll and Guernsey, makes comparison of yields no guide to profits. Rodewald(2), working on Schmidt's(3) data, has shown that, on the average, within a breed the larger an animal the greater is the yield of milk, and these results have been confirmed by Woll(4) and Peters(5). Grady(6), Nevens(7) and Beck(8) have also shown that for the production of milk the larger animal is the most economical, but that this does not hold when the production of butter-fat is considered.

Local conditions play a considerable part in determining the particular month in which the maximum or minimum yields are obtained. For instance the very low yields of cows calving in July and August in Essex is possibly brought about by the low rainfall of the district affecting the supply of succulent food in the autumn. In Norfolk the maximum yield is obtained by cows calving in October, while in N. Somerset this maximum is not reached until January; this is probably due to the more ample provision of roots in the winter feed in Norfolk keeping the milk flow going until the grass comes in spring, whereas in Somerset the small supply of roots is sufficient only to keep the flow going from January until the cows are turned out.

In order to determine more exactly the way in which the month of calving affected the yield, it was decided to plot the lactation curves of cows calving in different months; the records of the Penrith Milk Recording Society were selected for this, as the difference between the yield of spring and autumn calvers in this district was very large.

The records on which the rest of this paper is based were lactation records and not yearly ones (Oct. 1st-Oct. 1st), hence the figures given in Tables A (above) and I (below) do not agree in detail, although the variation due to month of calving is much the same in each case. In particular the August yields in the two tables are very different; towards the end of the milk recording year, the figures in Table A become unreliable owing to the increasing proportion of the milk being associated with a previous lactation period, the calving for which tends to fall in an earlier month than the one in which it is grouped.

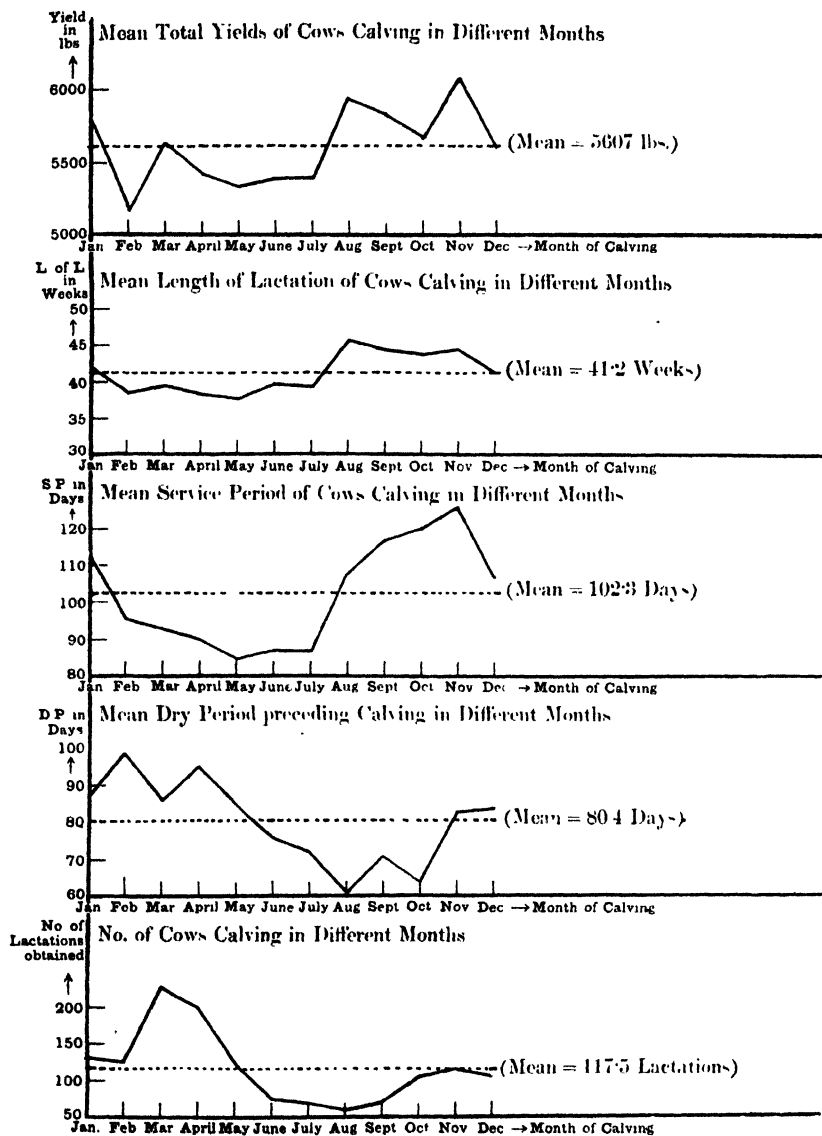


Fig. 1.

II. MONTH OF CALVING.

Table I gives the mean totals, length of lactations, service periods, and dry periods of all cows calving in the different months, and also the number of lactations obtained.

Table I.

	Jan. calvers	Feb. calvers	March calvers	April calvers	May calvers	June calvers	July calvers
Total yield (lbs.) ...	5808	5169	5625	5420	5343	5384	5396
Length of lactation (weeks) ...	42.0	38.5	39.4	38.1	37.8	39.7	39.2
Service period (days) ...	113	96	93	90	85	87	87
Dry period (days) ...	87	99	86	95	85	76	72
No. of lactations ...	130	125	229	200	122	74	69

	Aug. calvers	Sept. calvers	Oct. calvers	Nov. calvers	Dec. calvers	Means (Jan.—Dec.)
Total yield (lbs.) ...	5949	5831	5677	6077	5604	5607
Length of lactation (weeks) ...	45.7	44.4	43.8	44.4	41.1	41.2
Service period (days) ...	108	117	120	126	107	102.3
Dry period (days) ...	61	71	64	83	84	80.4
No. of lactations ...	60	70	106	118	107	117.5

These figures are shown graphically in Fig. 1.

The curve of the totals sinks very rapidly to a minimum value for February calvers, is low all the summer until August, when it suddenly rises, and remains high for the remainder of the year—reaching a maximum in November.

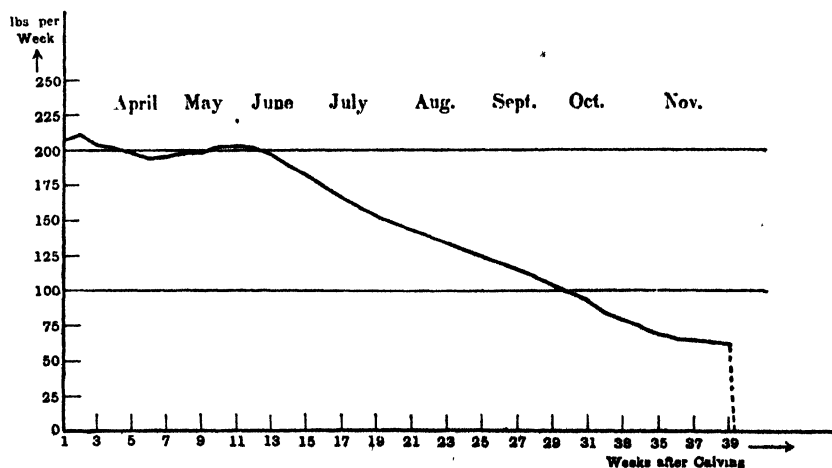


Fig. 2. Mean Lactation Curve—MARCH CALVERS. (Mean Total Yield = 5625 lbs.)

This variation was to a great extent explained by the mean lactation curves which were prepared, for all the cows calving in each month.

These curves showed a gradual change of shape from month to month and those for March, June, August and November calvers are given as being fairly representative of the different types (Figs. 2-5).

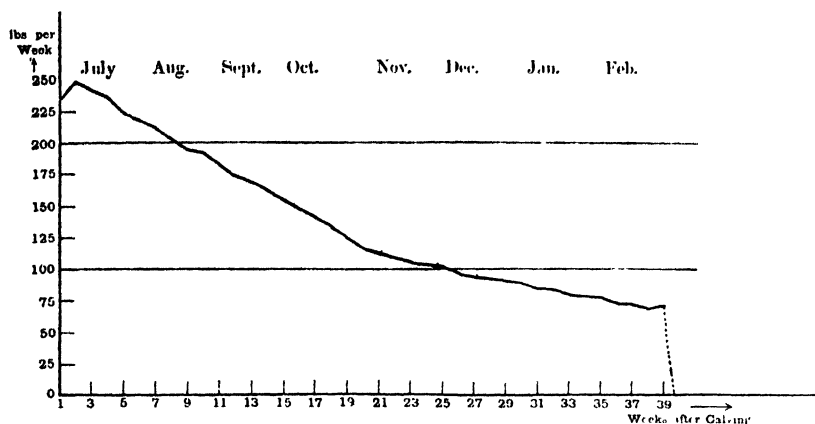


Fig. 3. Mean Lactation Curve—JUNE CALVERS. (Mean Total Yield 5384 lbs.)

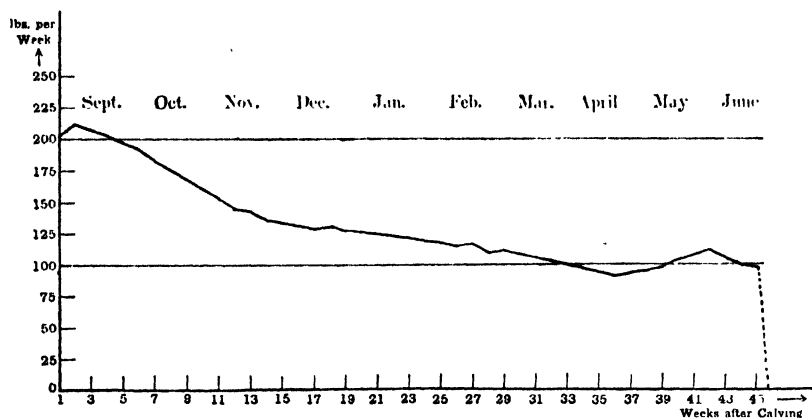


Fig. 4. Mean Lactation Curve—AUGUST CALVERS. (Mean Total Yield 5949 lbs.)

The most striking point of the curves is the rise which occurs at the end of May—when the grass is young and succulent; during the remainder of the summer, when the grass is fibrous, more bulky and less digestible, the yield falls rapidly. It will be noticed that cows calving in the early summer give a very high maximum and then tend to fall off rapidly.

August calvers are seen on the average to milk right through the winter and to benefit by the young grass in May—the lactation lasting

just over this period. As will be seen later these cows fall into two divisions—those which are served soon after calving and dry off before the following May (these are very poor yielders) and those which have long service periods, and milk right over the following spring, being, on the average, very high yielders.

Cows calving in August, September and October tend to dry off immediately after the “spring rise”; November calvers, however, on the average milk right through the summer.

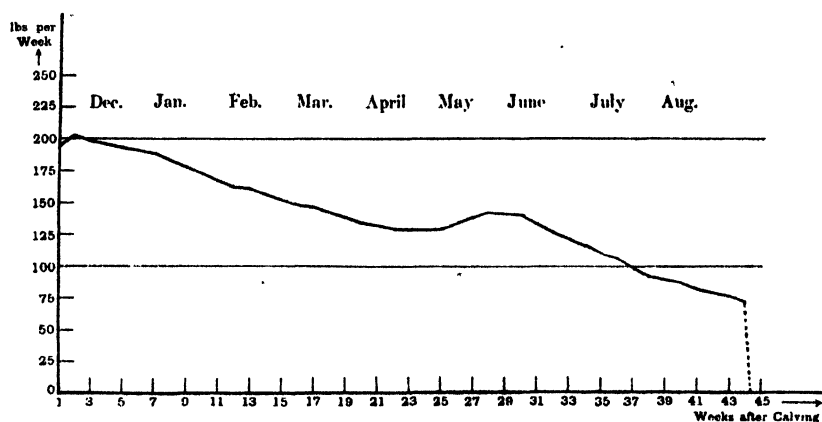


Fig. 5. Mean Lactation Curve—NOVEMBER CALVERS. (Mean Total Yield—6077 lbs.)

Further light is shed on the variation of the mean totals of cows calving in different months by the two curves given in Fig. 6, the first of which gives a measure of the actual yield of all cows during different calendar months, and the second the rate of rise or fall of yields at different times of the year.

The mean monthly lactation curves were divided into periods of four weeks that corresponded most nearly with the ten calendar months next succeeding that of calving. For the first curve the total yield during each of these “4 weekly” periods was taken and so figures were obtained for the amount of milk: (e.g.) June calvers give in the following Oct., and so on. In this way 10 totals were obtained for October from the different lactation curves of cows calving in the months December to September. The mean of these 10 totals was taken as a fair criterion of the value of October as regards the actual amount of milk given. Similarly figures were obtained for all months; by dividing by 4, the mean weekly yield in each month was obtained.

For the second curve the mean yield of the first week of each period

was subtracted from that of the last; this gave a negative figure for a drop in yield and a positive one for a rise—i.e. a rise or fall during three weeks. The mean rise or fall in each month was then found as above—and converted into lbs. per week, by dividing by 3.

Neither of these curves can be taken to give a real, intrinsic value to each month, as regards milk production, for in both the figures are all influenced by the ones preceding them—but together they explain, in a great measure, the variation in the mean totals obtained for cows calving in each month.

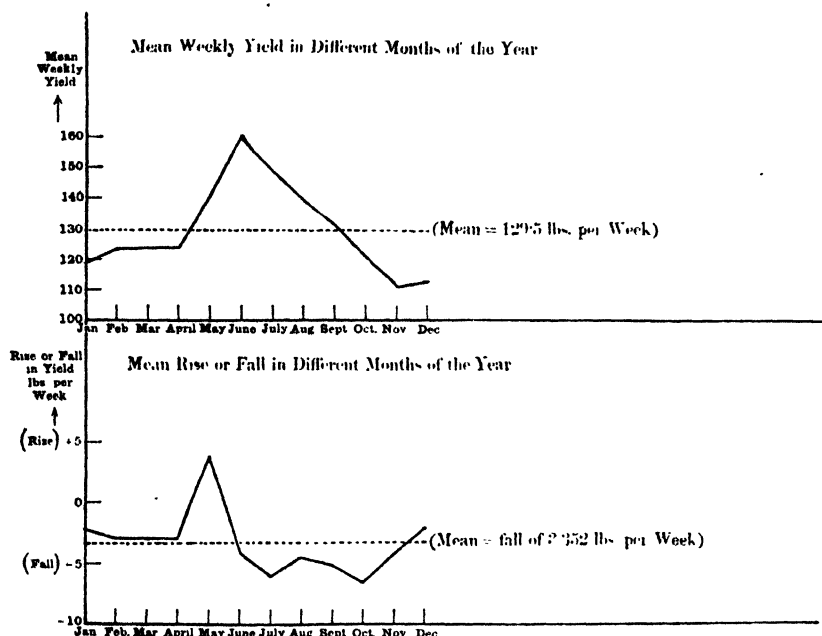


Fig. 6.

It will be seen that the amount of milk given is high from May to September and low in winter; on the other hand yields fall off much less in winter than in summer and autumn.

Immediately after the rise which occurs in May and the beginning of June, the drop is very sudden, due to the fact that the pastures get dry and parched and the grass hard and fibrous. Yields fall still more quickly in October when the cow is adapting herself to winter conditions; this must be the explanation of the fact that yields are so high for cows calving in November—they are already adapted to winter conditions,

and they give a steady flow of milk which only decreases very slowly throughout the winter; they do not fall to any considerable extent until the following June or July. That a cow yields more if she calves after winter feeding commences, than if calving took place just before the change, is probably due to the fact that, in the latter case, the change occurs at a time when she is actively draining on her body substance to supply the milk flow, for Haecker⁽⁹⁾ has shown that during the early stages of lactation the body weight of cows decreases rapidly. It will be seen from Table IV (below) that the maximum daily yield of cows calving in October is abnormally low.

The period during which the milk falls rapidly (July) comes earlier in the lactation as we proceed from November to December to January to February calvers, with the result that yields are lowered.

March calvers are giving very nearly their maximum when turned out to grass, so that they yield very much more during the first part of their lactation than do February calvers—accordingly their total yield is higher.

The variation of totals from month to month (*i.e.* of calving) is considered further on pp. 94 and 97.

Variation.

The following table gives the standard deviation, probable error of the mean, and coefficient of variation of the total yields of all cows calving in the different months (means given in Table I).

Table II.

Month of calving	Standard deviation totals	Probable error of mean of totals	Coefficient of variation of totals
January ...	1888 lbs.	112 lbs.	34.2
February ...	1582	95	30.6
March ...	1688	75	30.0
April ...	1806	86	33.3
May ...	1789	109	33.5
June ...	1874	147	34.8
July ...	2070	168	38.3
August ...	1889	164	31.7
September ...	1921	155	32.9
October ...	1921	126	33.8
November ...	1849	115	30.4
December...	1830	119	32.6

These coefficients of variation for total lactation yields are much the same as those obtained by Gavin⁽¹⁰⁾, who found a variation of 31.7 for complete lactations; they are above that obtained by Gowen⁽¹¹⁾—25.6 for an eight months' lactation; his low figure is probably due to the limit

imposed on the length of the lactation and to the fact that all the lactations were made in one herd.

In the first column of the following table is shown the difference between the mean yields for successive months of calving, and in the second the ratio of these differences to their standard errors. It is interesting to note that the nearest approach to actual significance is made by the drop in yield for February calvers.

Table III.

	Difference between mean yields	Difference - its standard error
February-January ...	- 639 lbs.	2.93
March-February ...	+ 456	2.54
April-March ...	- 205	1.21
May-April ...	- 77	.37
June-May ...	+ 41	.15
July-June ...	+ 12	.04
August-July ...	+ 553	1.59
September-August ...	- 118	.35
October-September ..	- 154	.52
November-October ...	+ 400	1.58
December-November ..	473	1.93
January-December ...	+ 204	.84

The coefficients of variation of the lengths of lactation in different months lie between 22 and 24.

For the mean weekly yields as given by the monthly lactation curves it was found that the average coefficients of variation were approximately

26	for weeks	1-9	after calving
27	..	..	10-19
31	..	..	20-29

After 30 weeks they became very variable and appeared to tend towards a value of about 40.

Such a high degree of variation is by no means uncommon with milk yields and other allied subjects. Maynard and Myers⁽¹²⁾ found that when cows were selected in the same stages of lactation and having approximately the same yield, the coefficient of variation of the daily yield over a two weeks' period lay between 9.5 and 17.5, with an average of 11.9. Pearl and Miner⁽¹³⁾ were able to reduce the coefficient of variation in the average weekly yield to 17.08, by separating cows into age groups; "lumped" together the coefficient was 20.82—which is below that found in the present paper. They suggest that about half the variability is due to genetic and half to environmental causes.

Maximum yield.

It has been claimed that a good estimate of a cow's yield in a lactation may be obtained by multiplying her highest daily yield by a certain factor—approximately 200 in winter calvers and 180–190 with summer calvers(10). Correlation tables were drawn up between the individual maximum daily yield and the total lactation yield, for all cows calving in each month, with the following results:

Table IV.

Month of calving	Mean total yield	Mean individual max. daily yield	Correlation coefficient	Factor, Total Max.
January ...	5808 lbs.	32.5 lbs.	+ .73 \pm .028	178.6
February ...	5169	31.1	+ .68 \pm .032	166.2
March ...	5625	34.0	+ .67 \pm .024	165.4
April ...	5420	35.2	+ .78 \pm .021	154.0
May ...	5343	37.4	+ .69 \pm .032	142.9
June ...	5384	37.1	+ .61 \pm .049	145.1
July ...	5396	35.6	+ .74 \pm .036	151.6
August ...	5949	32.0	+ .46 \pm .069	185.6
September ...	5831	31.8	+ .58 \pm .053	183.4
October ...	5677	29.8	+ .72 \pm .032	190.5
November ...	6077	30.7	+ .78 \pm .024	198.0
December ...	5604	30.5	+ .78 \pm .026	183.7

The results do not appear to accord with the claim mentioned above, there being a very considerable variation in the factor necessary to estimate totals from maxima in different months of calving—it is very much lower for the summer months. Tocher(14) has shown that the total yield per lactation varies very closely with the number of weeks the cow remains in milk and Vigor(15) that there is no significant correlation between the duration of lactation and the average weekly yield of milk.

It is interesting to note the drop of the correlation coefficients in August and September—due to the fact that many cows giving a small maximum maintain their flow till after the flush of grass next spring and so give a fair total yield, whilst others, served soon after calving, yield well to start with but dry off before the following spring and hence give a low total. The yield of these cows depends to a very large extent on the time at which they are next put to the bull.

III. EFFECT OF SERVICE.

The service period is, on the average, short in summer and long in winter. It has been found that cows come on heat more often in winter than in summer, but that they are "on" for a much shorter time, and therefore are very often "missed." Hence it is more difficult for the farmer

Table V. Correlation between total lactation yield and service period.

[illegible]

to get his cows in calf in the cold months than in the hot—a fact which agrees with the variation of the mean service periods for the several months, given in Table I.

Table V is a correlation table drawn up between service period and total yield; all lactations are included.

The correlation coefficient = $+0.33 \pm .016$.

The relation between service period and total yield is by no means linear, the yield rising at first more rapidly and then more slowly, as the service period is increased, and apparently tending to a limit. This suggested that a curve might be fitted to the means of columns, of the form

$$y = A - Be^{-cx},$$

where y is the yield and x the service period.

Trial gave the equation

$$y = 8.5 - 4.25e^{-.0044x}.$$

The curve is given in Fig. 7 and will be seen to give a fair fit to the data.

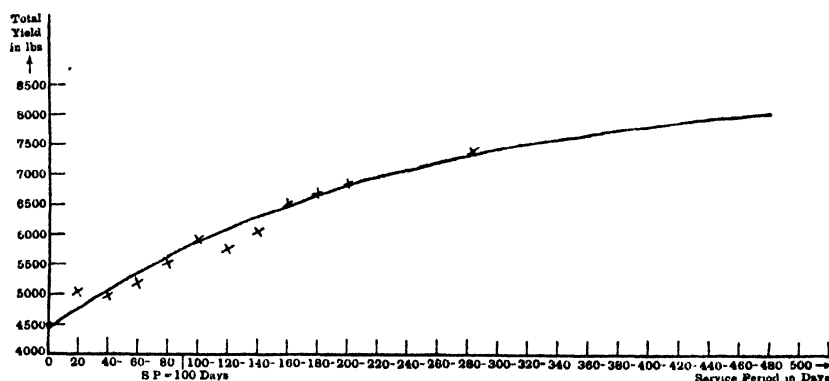


Fig. 7. Effect of Service on Total Yield.

The mean service period of all cows was found to be

$$100.7 \pm 1.11 \text{ days.}$$

Accordingly a period of 100 days was taken as being a normal service period and was selected as a standard; it will be noticed that cows served 100 days after calving, will calve again at about the same time (2–3 weeks later) next year. From the smoothed curve the mean total corresponding to this service period = 5760 lbs.

The second column of Table VI gives the mean totals obtained from the smoothed curve for cows with the service period stated; the next column gives the factor by which this total must be multiplied in order

to make it 5760 lbs.—the value for the standard. In the last column is given the percentage correction for each period.

E.g. a cow gives 6000 lbs. with a service period of 13 days; under normal conditions (service period = 100 days) therefore she would have given

$$6000 - \frac{30}{100} \times 6000 = 7800 \text{ lbs.}$$

Table VI. *Corrections to total yield for service period.*

(Standard service period = 100 days: value of yield for 100 days = 5760 lbs.)

(1)	(2)	(3)	
Service period	Corresponding mean total from smoothed curve	5760 total from (2) (correction factor)	Percentage correction to apply
0 - 19 days	4427 lbs.	1.301	+ 30 %
20 - 39	4770	1.207	+ 21
40 - 59	5084	1.133	+ 13
60 - 79	5372	1.072	+ 7
80 - 99	5635	1.022	+ 2
100-119	5876	.980	- 2
120-139	6097	.944	- 6
140-159	6300	.914	- 9
160-179	6485	.888	- 11
180-199	6655	.866	- 13
200-219	6830	.846	- 15
220-239	6952	.828	- 17
240-259	7083	.813	- 19
260-279	7202	.799	- 20
280-299	7311	.788	- 21
300-319	7411	.777	- 22
320-339	7503	.768	- 23
340-359	7587	.759	- 24
360-379	7664	.751	- 25
380-399	7734	.744	- 26
400-419	7799	.738	- 26
420-439	7858	.733	- 27
440-459	7912	.728	- 27
460-479	7961	.723	- 28
480-499	8007	.719	- 28

A cow's yield may vary, we see, by as much as ± 30 per cent. according as she has a very long or a very short service period; this is due largely to the fact that there is, of course, a close relation between the length of this period and the length of her lactation. The growth of the foetus, partly through requiring nutrition which would otherwise go to milk production, and partly through an internal secretory effect on the mammary gland, lowers her yield and finally stops it altogether.

To ascertain the effect of this lowering of her yield and the time at which it begins to operate, lactation curves were prepared for

- (a) all cows with a service period of 220 days and over;
- (b) " " " from 60 to 79 days;
- (c) " " " " 40 to 59 ..

For the purposes of comparison with the other two, the first may be considered as unserved.

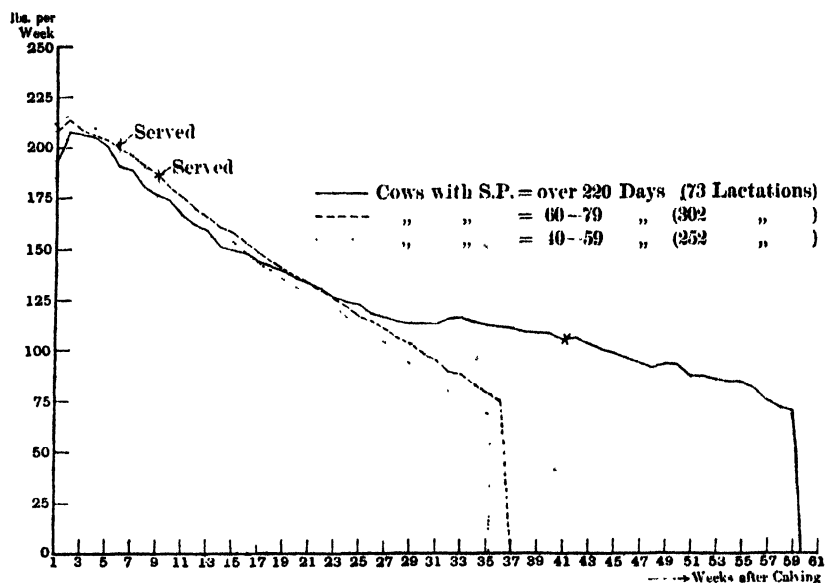


Fig. 8. Effect of Foetal Growth on Milk Yield.

The curves (Fig. 8) are not, however, strictly comparable, as the cows with short service periods are principally summer calvers—those with long ones, winter calvers. Hence the differences between the curves are due partly to foetal growth and the attendant secretions, and partly to the fact that there are different proportions of cows in each, calving in the various months of the year.

Accordingly the three curves were all corrected to the “mean curve”—i.e. the mean of the 12 monthly lactation curves. Each week of each curve was corrected separately.

For instance the curve for “service period = 40–59 days” was given by 252 cows of which

7 per cent. were January calvers	10 per cent. were July calvers
6 " " February "	6 " " August "
12 " " March "	5 " " September "
18 " " April "	6 " " October "
13 " " May "	5 " " November "
7 " " June "	5 " " December "

and these percentages varied as soon as cows began to dry off.

Hence to correct the first week's yield of this curve, 7 per cent. of the mean first weekly yield of January calvers was added to 6 per cent. of that of February calvers and so on. This total gave what might be expected to be the mean yield during the first week of this proportion of cows calving in each month. Therefore to correct our figure for the first week of the curve to compare with the "mean curve," it had to be multiplied by the factor

$$\frac{\text{Total of mean curve for first week}}{\text{Total obtained above}}$$

This factor was obtained for every fifth week and was found to vary gradually, so that a curve could be fitted and the values for the other weeks read off.

In this way each of the three curves given in Fig. 8 was corrected to the "mean curve"—and so became comparable. The corrected curves are given in Fig. 9.

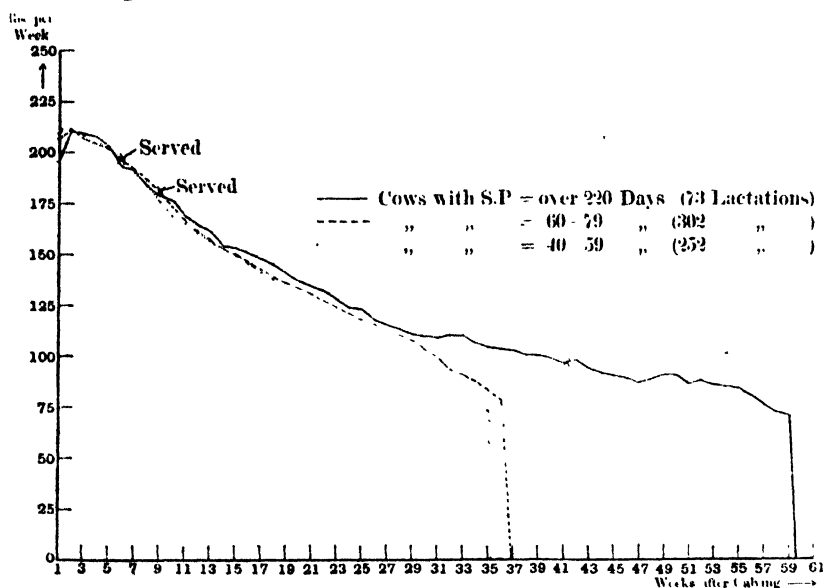


Fig. 9. Effect of Foetal Growth on Milk Yield (corrected curves).

It appears that there is a slight fall in yield immediately after service, and that this lower level is maintained for about 20 weeks, when the cows begin definitely to dry off.

Taking the mean weekly yields of each of the others for the first nine weeks after service, from that of unserved cows over the same periods we get the following results:

(1) Mean weekly yield of unserved cows during weeks 7-15

after calving = 170.2 lbs.

Mean weekly yield of cows with service periods = 40-59

days (served at sixth week) = 167.4 „

Here the drop = 2.8 lbs., and its standard error = 1.97 lbs., *i.e.* drop = $1.4 \times$ its standard error.

(2) Mean weekly yield of unserved cows during weeks 10-18

after calving = 158.1 lbs.

Mean weekly yield of cows with service period = 60-79

days (served at ninth week) = 154.5 „

Here the drop = 3.6 lbs., and its standard error = 1.77 lbs., *i.e.* drop = $2.03 \times$ its standard error.

In each case the drop is not large compared with its standard error; but it seems clear, from the uniform trend of the curves, that it is, in fact, real.

Fig. 10 shows the mean rise or fall of the two curves for cows with service periods of "40-59 days" and "60-79 days" respectively, above or below that of unserved cows, for the five weeks preceding service and for the 29 weeks succeeding it, at the end of which period, they are, on the average, dry.

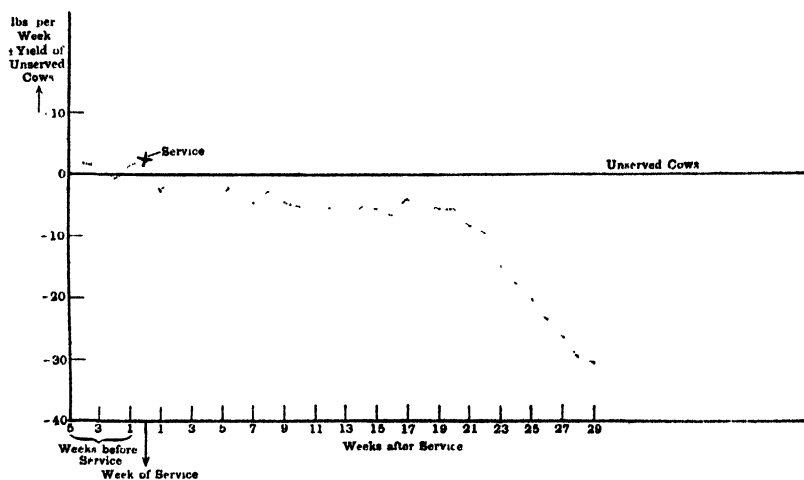


Fig. 10. Fall in Yield due to Foetal Growth.

It is interesting to note that recent work¹ suggests that there is a very considerable change in the composition of the secretion, which can be obtained from the mammary glands of heifers during their first pregnancy,

¹ Paper in course of preparation, continuation of work by Woodman and Hammond (60).

at, or about, the twentieth week after service. It would appear that some definite physiological factor comes into play at this period, which seems to be correlated with a definite fall in milk yield.

It seems probable that the slight fall immediately after service is due to natural causes resulting from the growth of the uterus and its contents, and that the definite drying off at 20 weeks after service is brought about by the internal secretions from the reproductive organs initiating an anabolic phase of growth in the mammary gland.

Variation of effect of service with month of calving.

It would appear probable that the influence of the length of the service period on the total yield varies according to the month in which the cow calves; unfortunately the data available were insufficient to give reliable corrections.

Curves similar to Fig. 7 were prepared for cows calving in

(a) April (200 lactations);

(b) August and September (130 lactations).

The former gave a curve of the same form as that used above (Fig. 7) though the points obtained do not approximate to it very closely. For the second it was found that the yields of cows with service periods falling in the first five 20-day periods lay very close to a curve of the same form, but that there was then a sudden jump, suggesting a curve of the nature of that given in Fig. 11.

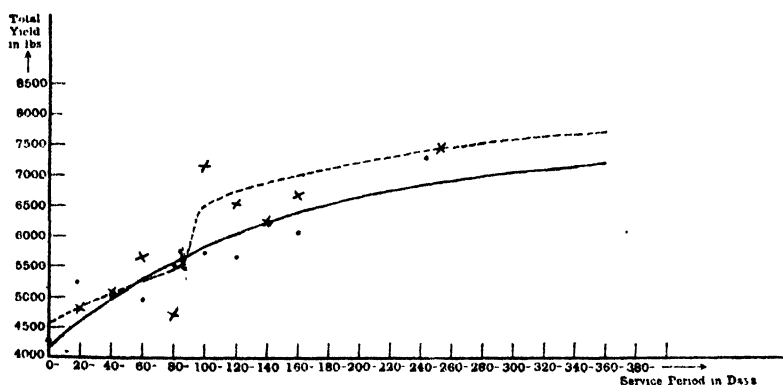


Fig. 11. Comparison of Effect of Service Period on Total Yield with cows calving in
 (a) April (Curve — Pts. obtained ●)
 (b) August and September (Curve - - - Pts. obtained ×)

The explanation of the break in the second curve must lie in the fact that cows with service periods of less than 100 days are, on the average,

dry before the following spring, whilst those with longer service periods get the benefit of the "spring rise."

It is probable that considerably increased accuracy could be obtained by applying different corrections for each month of calving, if sufficient data could be obtained to give them definitely.

Correction of month of calving totals for time of service.

The curves given in Fig. 1 for the mean totals and service periods of cows calving in each month show a marked resemblance—the variation of the former being to a considerable extent dependent on that of the latter. Hence corrections for month of calving, on the basis of the totals alone, would be invalid when used with those for the length of the service period.

The mean totals of all cows calving in each month were, therefore, corrected for service period on the same principle as was used above to correct lactation curves (p. 90), with the following results:

Table VII.

Month of calving	Mean total (uncorrected)	Mean total (corrected for service period)
January ...	5808 lbs.	5661 lbs.
February ...	5169	5147
March ...	5625	5662
April ...	5420	5519
May ...	5343	5546
June ...	5384	5619
July ...	5396	5606
August ...	5949	5959
September ...	5831	5744
October ...	5677	5526
November ...	6077	5820
December ...	5604	5476
Mean ...	5607	5607

Corrections were also made in the opposite direction—i.e. the totals in the various 20-day service periods were corrected for the month of calving; this was found, though, to have no appreciable effect on the results obtained before.

IV. AGE.

Fig. 12 shows the mean and median service periods of 1st calvers, 2nd calvers, etc.; the former is greatly influenced by a small proportion of cows which have very long periods (300–500 days) and the latter is probably the better average.

It will be seen that the service period becomes shorter with age until after the 3rd or 4th calf, when it begins to increase again, until after the

6th or 7th calf it is longer than after the first. This curve probably represents the vigour or "curve of life" of the animal; the cow reaches its prime as regards reproductive energies (but not milk flow) at the 3rd or 4th lactation (*i.e.* about six years old). Before the 3rd lactation the full reproductive activities of the animal are curtailed by coincident growth and after this time senile decay gradually begins.

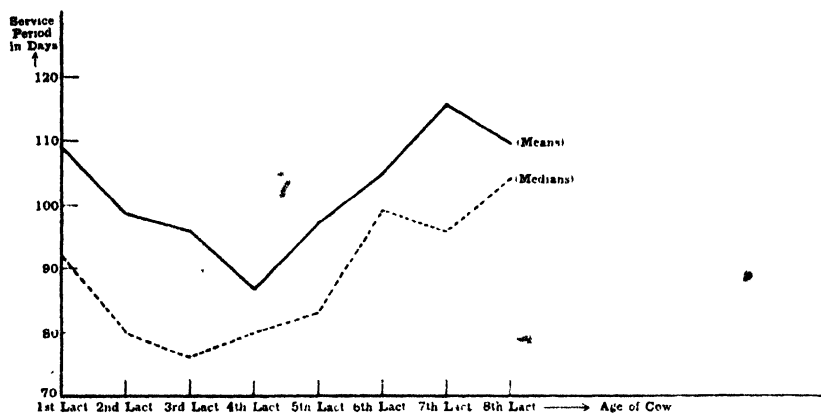


Fig. 12. Variation of Service Period with Age.

The curves show that no accurate measure of the variation which a cow's yield undergoes as she gets older could be obtained without first correcting her total yields for the service periods associated with them. It was found that the period of rest preceding calving (*i.e.* the dry period) did not vary in any definite way with age and for this factor no corrections were necessary.

Accordingly to ascertain the rise or fall of yield with age all totals were first corrected for the month of calving and for the service period. Then the means of the 1st and 2nd lactation totals of all cows, of which these two were known, were found; the difference between these means was then expressed as a percentage of the 1st lactation mean total. The same was done with cows of which the 2nd and 3rd lactation totals were known—the difference being expressed as a percentage of the 2nd lactation mean total yield and so on. By this means differences due to selection have been eliminated; many authorities who have estimated the age changes from "lumped" data have included also selection by the farmer with age.

The results are given in Table VIII together with those obtained by treating uncorrected totals similarly.

Table VIII.

(1)	(2)	(3)	(4)	(5)
	Mean totals (corrected) lbs.	Rise or fall as percentage of former (corrected)	Results as (3) from uncorrected totals	No. of cows
1st lactation	4909	+ 10.5 % \pm 1.8 %	+ 9.5 % \pm 2.0 %	253
2nd "	5425			
2nd lactation	5746	+ 10.7 % \pm 2.0 %	+ 9.7 % \pm 2.3 %	154
3rd "	6359			
3rd lactation	6595	+ 0.2 % \pm 2.2 %	+ 1.4 % \pm 2.7 %	99
4th "	6610			
4th lactation	6655	+ 6.5 % \pm 2.7 %	+ 4.2 % \pm 3.4 %	46
5th "	7088			
5th lactation	7782	5.4 %	-	21
6th "	7364			
6th lactation	6779	0.3 %	-	8
7th "	6759			
7th lactation	7382	6.0 %	-	8
8th "	6941			
8th lactation	5376	12.1 %	-	2
9th "	4723			

After the first five lactations the numbers of lactations became so small that reliable results could not be expected.

Putting the first lactation yield as 100, the next four are as follows:

Table IX.

	Corrected	Uncorrected
1st lactation yield	100.0	100.0
2nd " "	110.5	109.5
3rd " "	122.3	120.1
4th " "	122.5	121.7
5th " "	130.3	126.8

From Table VIII it will be seen that the probable error, in each case, is smaller with corrected totals, than with uncorrected ones: from Table IX we see that with uncorrected totals all subsequent lactations are reduced relatively to the first—a fact that might be expected from a perusal of Fig. 12 showing the variation of service period with age.

Accordingly variation with age was found from the figures obtained from corrected totals.

Taking an average 1st lactation yield as 4909 lbs. we get the 2nd by taking 110.5 per cent. of this; the 3rd is 122.3 per cent. of the first and so on. The totals obtained thus are given in the first column of Table X.

To obtain some continuous figures for purposes of correction, the mean (corrected) yields were roughly smoothed by a graph, giving the figures in the second column of Table X; the adjusted corrections for

age are shown in the third column—the application of these corrections gives an estimate of the 5th lactation yield (which appears to be the highest) from each of the first four.

Table X.

	Mean yield as found	Value from smoothed curve	Corrections for age (to estimate 5th lactation yield)
	lbs.	lbs.	%
1st lactation	4909	4930	+ 30
2nd "	5424	5435	+ 18
3rd "	6004	5840	+ 10
4th "	6016	6167	+ 4
5th "	6407	6429	—

Corrections to monthly totals for age.

The mean totals obtained for the different months of calving are considerably influenced by an apparently purely adventitious factor—namely the ages of the cows whose lactations happen to have been available; the numbers of lactations obtained for each month were insufficient to neutralise this error of sampling.

Table XI gives the mean monthly yields (*a*) uncorrected, (*b*) corrected for service period (Table VII), (*c*) corrected for service period and age. The last column gives the corrections to apply for month of calving; the standard has been chosen as the mean of all months and coincides approximately with the yields of January, June and July calvers.

Table XI.

Month of calving	Uncorrected mean yields	Mean yields corrected for service period	Mean yields corrected for service period and age	Corrections for month of calving
	lbs.	lbs.	lbs.	%
January ...	5808	5661	5596	—
February ...	5169	5147	5097	- 10
March ...	5625	5662	5504	+ 2
April ...	5420	5519	5446	+ 3
May ...	5343	5546	5471	+ 2
June ...	5384	5619	5565	—
July ...	5396	5606	5568	—
August ...	5949	5959	6101	- 8
September ...	5831	5744	5839	- 4
October ...	5677	5526	5664	- 1
November ...	6077	5820	5951	- 6
December ...	5604	5476	5495	+ 2
Means ...	5607	5607	5607	

These are shown graphically in Fig. 13.

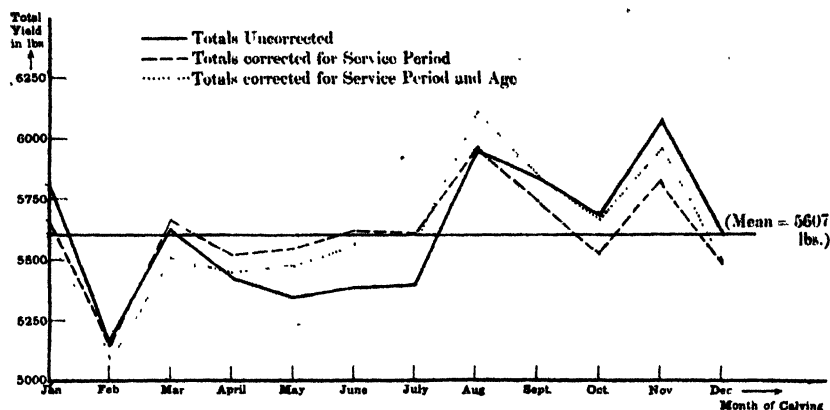


Fig. 13. Variation of Totals with Month of Calving.

V. EFFECT OF THE DRY PERIOD.

The curve in Fig. 14 gives the result of a simple correlation table, drawn up between total yields and the period of rest (dry period) before calving. It is based on 711 lactations.

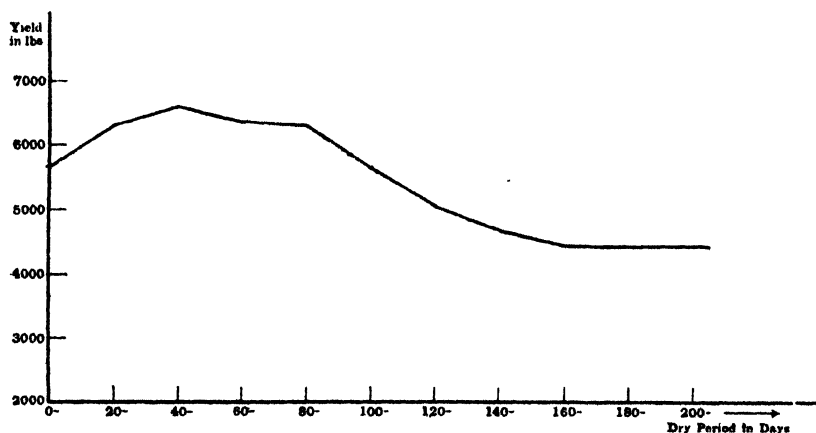


Fig. 14. Variation of Totals (uncorrected) with Dry Period.

This curve appears to be affected by three separate factors:

- (1) Any effect which the dry period may have on yields.
- (2) The fact that great numbers of good milkers are such because they maintain their flow until a short time before calving again, whilst poor milkers dry off much sooner.
- (3) The relation which appears to exist (and which, as shown below, certainly holds with these particular lactations) between the dry period

and service period; this relation is that cows with a short period of rest before calving have, on the average, a long period after calving, before they are served again.

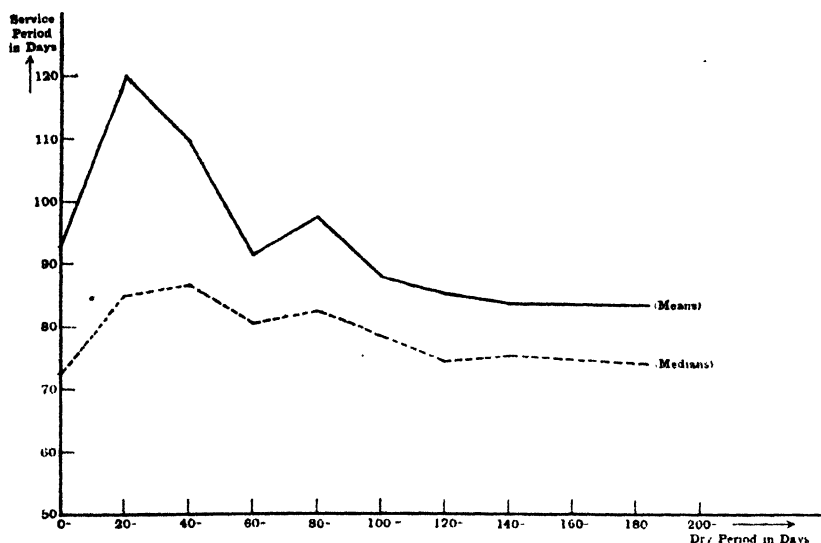


Fig. 15. Relation between Dry Period and following Service Period.

The correlation coefficient between length of service period and length of dry period = -0.13 ± 0.025 .

Hence to obtain an accurate measure of the effect of the dry period on the subsequent yield, we must first correct totals for service period, and must then consider each cow separately. The method adopted was as follows.

All cows were taken whose first and one or more subsequent lactations (with dry periods) were known. The totals of all lactations were corrected for month of calving, service period and age, and subsequent yields were expressed as \pm a percentage of the 1st lactation yield. This latter may be considered as having an indefinite dry period—allowance for which has been made when correcting for age: the percentages show whether or not a cow has fulfilled the promise of her performance as a heifer.

A correlation was then drawn up between these percentages, and the length of the dry periods preceding the lactations from which they were derived.

It is recognised that a 1st lactation yield is always a bad standard on account of its very great variability (it was found that the coefficients

of variation of the totals given in column (2) of Table VIII. decrease steadily and considerably—from 28·5 to 20·1—as we proceed from the first to the fifth lactation). With sufficient data, however, the errors arising through this variation should become negligible.

Only 408 observations could be found for the correlation table and this made it somewhat irregular.

The correlation coefficient = $+ \cdot 22 \pm \cdot 032$.

The mean percentages above or below 1st lactation yield of cows grouped in 20-day dry periods were very irregular; by taking groups of 40-day dry periods the means were found to be:

Dry period	Mean percentage
0- 39 days	- 6·3 per cent. \pm 1·8 per cent.
40- 79 „	+ 3·9 „ \pm 1·4 „
80-119 „	+ 7·0 „ \pm 1·5 „

That is to say the relative yields of these cows are as follows:

Table XII.

Dry period	Relative value of yield	Yield with that for period "0-39 days" as 100
0- 39 days ...	93·7	100·0
40- 79 „ ...	103·9	110·9
80-119 „ ...	107·0	114·2

It would appear that a cow's yield is considerably lowered by a very short dry period, but not greatly increased by a very long one. The curve in Fig. 16 is suggested as representing the effect of the dry period on the yield.

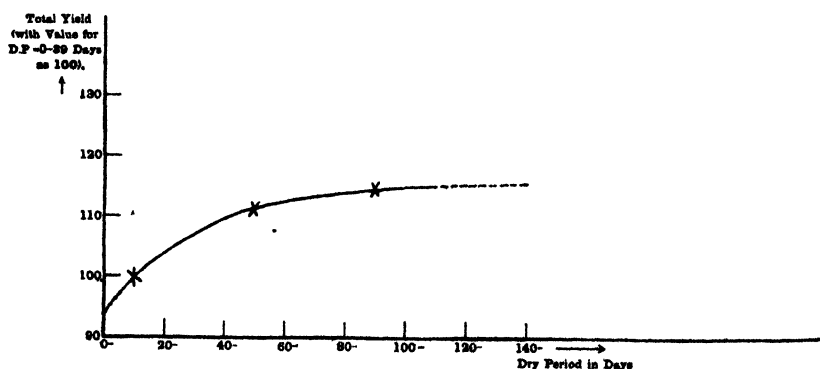


Fig. 16. Effect of Dry Period on Subsequent Yield.

There are two weaknesses in this curve:

(1) There is, in the data, no indication of a further fall in yield if the dry period is lowered from "20-39" days to "0-19" days.

(2) There is some evidence of a further rise associated with dry periods of over 120 days; in 78 lactations this rise was found to be 5.9 per cent. \pm 2.5 per cent.

The mean length of dry period of all lactations, in which it was known, was 85 days—this was accordingly used as a standard. In the West of England (spring calving, grassland dairying with few, if any, roots), dry periods appear to be considerably longer than in the East, where the average would probably be from 50 to 60 days.

From Fig. 16 the value for totals corresponding with a dry period of 85 days = 113.5; the corrections for dry period are, then:

Table XIII.

Length of dry period	Correction to apply
0- 39 days	+13 %
40- 79 "	+ 2.5
80-119 "	—
Over 120 days	- 2

The problem was also attacked by another method; denoting the periods "0-39 days," "40-79 days," "80-119 days," by *A*, *B* and *C*, the totals given by the same cow after dry periods falling in these categories were compared; *i.e.* her yield after a dry period falling in *A* was compared with that after one falling in *B*, and so on. This gave three comparisons—*i.e.* between the effects of dry periods *A* and *B*, *B* and *C*, *A* and *C* respectively.

Many cows whose dry periods all fell into the same category had to be rejected, and consequently the number of lactations on which the work was based was regrettably small. No corrections were applied to the totals.

The results are shown in Table XIV.

Table XIV.

Mean excess of yield		lbs.	%	No. of observations
After Dry period	Over that after Dry period			
<i>B</i>	<i>A</i>	+714 \pm 235	+11.1 \pm 3.6	49
<i>C</i>	<i>B</i>	+259 \pm 164	+ 4.1 \pm 2.6	106
<i>C</i>	<i>A</i>	+913 \pm 314	+15.0 \pm 5.2	29

Putting, as before, the yield after dry period *A* as 100 we get

Dry period	Relative yield
<i>A</i>	100.0
<i>B</i>	111.1
<i>C</i>	115.6

and from the relation $C-A$, if

yield after *A* = 100.0,

then

yield after *C* = 115.0.

These results agree very closely with those obtained by the other method.

The total number of lactations extracted for this investigation was 1410; 483 of these were first calvers and of the others the dry period preceding was known in 711 cases; hence in 216 lactations the dry periods were not ascertainable. Under these circumstances any corrections applied to the mean monthly totals for the dry period would be untrustworthy.

VI. REDUCTION OF VARIATION.

The following corrections have been found for the four factors the study of which is the object of this investigation.

(A) *Month of calving.*

Month	Correction
	%
January	—
February	+ 10
March	+ 2
April	+ 3
May	+ 2
June	—
July	—
August	- 8
September	- 4
October	- 1
November	- 6
December	+ 2

(B) *Service period.*

Service period	Correction
	%
Days	
0- 19	+ 30
20- 39	+ 20
40- 59	+ 13
60- 79	+ 7
80- 99	+ 2
100-119	- 2
120-139	- 6
140-159	- 9
160-179	- 11
180-199	- 13
200-219	- 15
220-239	- 17
240-259	- 19
260-279	- 20
280-299	- 21
300-319	- 22
320-339	- 23
340-359	- 24
360-379	- 25
380-399	- 26
400-419	
420-439	- 27
440-459	
460-479	- 28
480-499	

(C) <i>Age.</i>		(D) <i>Dry period.</i>	
Age	Correction	Dry period	Correction
1st lactation	+ 30%	0- 39 days	+ 13 %
2nd "	+ 18	40- 79 "	+ 2.5
3rd "	+ 10	80-119 "	—
4th "	+ 4	120 (and	
5th "	—	over) "	- 2
6th "	—		

The figure obtained from a lactation by applying the above corrections is an estimate of the cow's yield, under normal conditions, when at her prime (which is taken to be at the 5th or 6th calf); normal conditions being defined as:

- (1) calving in January, June or July (*i.e.* "mean" months);
- (2) with a period of 100 days between calving and the next service;
- (3) with a period of rest before calving of 85 days.

When correction is to be made for all four factors these are the figures to apply, but where one factor only is considered the original "uncorrected correction" should be used as it will tend to have associated with it variations natural to the factor for which the correction is made.

As a means of testing the efficiency of the corrections the following methods were adopted.

The lactations of all cows available were taken of which the yields with the first three or more calves were known.

The following were obtained:

		No. of cows	No. of lactations
Cows with lactations	1 to 3	60	180
"	" 1 to 4	28	112
"	" 1 to 5	9	45
"	" 1 to 6	3	18
		<hr/> 100	<hr/> 355

The mean of all the yields of each cow was found and the variation of her several totals was expressed as \pm a percentage of this individual mean.

E.g. one cow gave four lactations the total yields in which were 6266 lbs., 5417 lbs., 5317 lbs., 4771 lbs.

The mean of these is 5443 lbs., and the variations are respectively,

$$+ 14\%, \quad - 0\%, \quad - 2\%, \quad - 12\%.$$

A frequency distribution was then drawn up of the 355 percentages thus obtained; from this were found the standard deviation and the semi-interquartile range—*i.e.* the range within which half of the observations fall.

These measures of variation of yields about the individual means were found for all totals.

- (a) Uncorrected;
 - (b) Corrected for month of calving and service period;
 - (c) Corrected for month of calving, service period and age;
 - (d) Corrected for month of calving, service period, age and dry period;
- with the results shown in Table XV.

Table XV.

		Semi-inter- quartile range	Standard deviation
(a) Uncorrected totals	... ..	10.24	16.41
(b) Totals corrected for	{ month of calving and service period }	9.90	15.97
(c) Totals corrected for	{ month of calving, service period, and age }	8.22	13.77
(d) Totals corrected for	{ month of calving, service period, age and dry period }	8.13	13.45

From this we see that the variation is reduced by applying all four corrections by about 20 per cent. of its original value. Of this reduction approximately:

- (1) 3 per cent. is achieved by corrections for service period and month of calving.
- (2) 15 per cent. is achieved by corrections for age.
- (3) 2 " " " " dry period.

It must be noted, however, that this does not give a good idea of the relative value of these corrections, as individual cows do not, generally, vary, to any large degree, their service and dry periods—that is cows tend to have all long or all short service periods and similarly for dry periods.

An individual may have, say, four service periods all between 150 and 200 days; corrections for these, whilst giving a much better estimate of the cow's ability, hardly reduce the variation, as measured above, at all.

Furthermore cows generally calve about the same time each year so that "month of calving" corrections have very little effect in many instances.

Taking a cow that gives with her fifth calf, under our standard conditions, 7000 lbs. of milk, we find from the corrections given, that her lactation yield might vary as follows with the various factors:

Calving in February	probable	yield=6364 lbs.
„ August	„ „	= 7609 „
With a service period of 10 days	„ „	= 5385 „
„ „ „ 410 „	„ „	= 9459 „
With a dry period of 10 days	„ „	= 6195 „
„ „ „ 130 „	„ „	= 7143 „

Her successive lactation totals, under normal conditions, being:

1st lactation	= 5385 lbs.
2nd „	= 5932 „
3rd „	= 6364 „
4th „	= 6731 „
5th „	= 7000 „

That is to say, the average maximum variations possible due to the four factors are (for a 7000 lbs. cow):

Service period ...	4074 lbs.
Age ...	1615 „
Month of calving	1245 „
Dry period ...	948 „

The results obtained above (Table XV) are a little disappointing, but it must be remembered that four, only, of the many factors influencing yields have been considered. Individual totals vary in every conceivable way. One cow may give a very big flow for a short time, whilst another maintains a moderate flow over a considerable period; the effect of the month of calving, of service, and possibly of the dry period, on these two cows would obviously not be the same. With all possible corrections the yields of a great number of cows fluctuate in perfectly inexplicable ways, causing large variations which, it would seem, are impossible to eradicate.

That a definite approach to the real milk producing value of the cows has been made by the application of the corrections found, is shown by the frequency curves (Fig. 17) obtained from the frequency distribution of percentage variation about the individual means of uncorrected totals and totals corrected for all four factors.

Taking the actual variation, and neglecting the sign, we get the curves shown in Fig. 18. The percentages had to be regrouped, to get all intervals the same size.

The distribution of the variation of corrected totals is much more regular than that of uncorrected totals, and the number of lactations which vary from the cow's mean yield by less than 5 per cent. is increased from 88 to 112—a rise of 27.3 per cent.

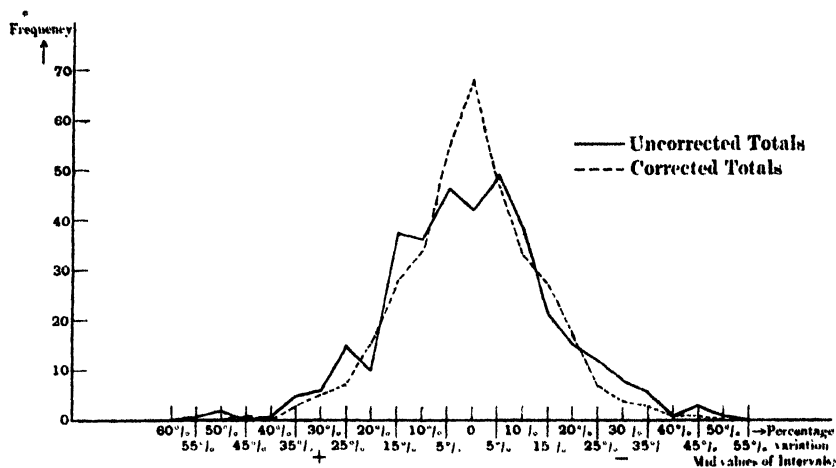


Fig. 17. Frequency curve of percentage variation of totals.

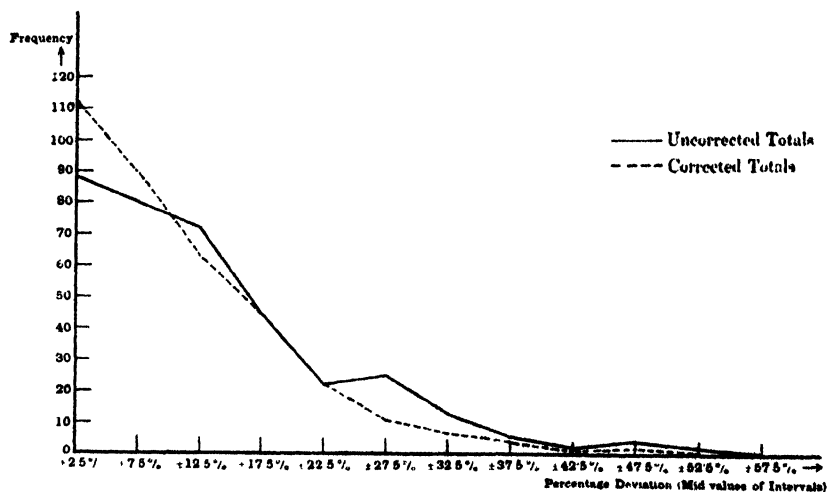


Fig. 18. Frequency curve of percentage deviation of totals from individual means.

It must, of course, be admitted that the process of correction is rough, and that more or less divergent results might be obtained by other methods, or by taking the corrections in a different order. The problem is really one in multiple correlation, there being no less than four variables

considered which all affect the yield—month of calving, service period, age, and dry period. But the correlations are not linear and the full solution of the correction problem would therefore be very difficult, even if the number of observations sufficed. It is only hoped that the results obtained give, at least, a first approximation to the truth.

VII. GENERAL DISCUSSION OF RESULTS.

(A) Month of Calving (pp. 80-86).

The results described in this Paper are in general agreement with those obtained by other investigators—which are shown in Table C; this should be compared with Tables A and I.

Table C. *Monthly variation in yield in different districts.*

Authority	District	No. of cows	Mean yield lbs. per year	Yield as lbs. \pm average yield					
				Jan.	Feb.	March	April	May	June
Wilson ⁽²⁵⁾	Yorkshire	484	6680	- 270	+ 110	+ 210	- 20	- 300	- 30
Wilson ⁽²⁵⁾	Ireland	811	7180	+ 38	+ 175	+ 110	- 850	- 1969	- 193
Petersen-Dalum ⁽²⁶⁾	Denmark	1472	7370*	+ 433	+ 153	+ 53	- 460	- 748	- 1028
Gavin ⁽¹⁰⁾	Essex	731	6700	+ 340	+ 320	+ 300	+ 120	- 30	- 630
Tocher ⁽¹⁴⁾	Ayrshire	3893	7500	- 240	- 260	- 230	- 490	- 450	- 590

Authority	District	No. of cows	Mean yield lbs. per year	Yield as lbs. \pm average yield					
				July	Aug.	Sept.	Oct.	Nov.	Dec.
Wilson ⁽²⁵⁾	Yorkshire	484	6680	- 510	- 10	- 540	+ 470	+ 30	+ 880
Wilson ⁽²⁵⁾	Ireland	811	7180	+ 209	- 538	+ 1364	+ 324	+ 1045	+ 295
Petersen-Dalum ⁽²⁶⁾	Denmark	1472	7370*	- 1570	+ 30	+ 580	+ 1179	+ 929	+ 452
Gavin ⁽¹⁰⁾	Essex	731	6700	- 900	- 1190	+ 300	+ 350	+ 450	+ 580
Tocher ⁽¹⁴⁾	Ayrshire	3893	7500	+ 510	+ 280	+ 520	+ 520	+ 420	+ 60

* Danish pounds.

Even when allowance is made for the small number of lactations on which some of the results have been calculated, it will be seen that variations exist between different localities. In Ayrshire, in particular, the highest yields are attained by cows calving earlier in the autumn than in other districts, which may be due to the higher feeding that takes place during winter months in this district. Goldschmidt *et al.* ⁽¹⁶⁾ have shown that by increasing feeding, the natural depression in milk production due to the progress of lactation may be checked. It would appear that the higher cows are fed during the winter months, the earlier in the autumn will the maximum yield be attained. Bartlett⁽¹⁷⁾ states that whereas heavy yielding cows give most milk in the autumn, low yielding ones give most if calved in the early spring, and this conclusion would

appear to be borne out by the figures given in Tables A and C, with the exception of the Penrith figures, but is open to the objection that the yearly yields in each case are due as much to feeding as to breeding differences. Thomson⁽¹⁸⁾, however, has shown that cows of inherited milking quality will suffer less diminution of milk secretion during a period of scanty feeding than cows not of good milking strains.

Tocher⁽¹⁴⁾ noticed, and the variation in Table II shows, that there were more high yields among cows which calved during the summer months than those which calved during winter, and this can be explained (as shown in Fig. 11) by variations in feeding and time of service, determining whether the summer calving cow holds her milk through the winter to take advantage of the flush of grass in the following spring, or is dried off under winter conditions.

For cows calving in the autumn months there is great scope for improvement of yields since at one or other of these months a sharp rise in yield from a large negative to a high positive value occurs. Calving should be regulated according to this critical time in each locality, so as to come after it, or the service periods of cows calving then should be adjusted (see Fig. 11) or additional feeding of these cows undertaken during the winter months.

Daily yield throughout the year.

Buckley⁽¹⁹⁾ has shown that in a Shorthorn herd in Berkshire the average daily yield varies each month as follows:

Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
90.3	94.6	94.7	97.5	118.2	120.8	114.7	106.5	99.0	93.1	85.3	86.1

These figures correspond to the curve shown in Fig. 6 with the exception that the flush in spring is more marked in May and comes slightly earlier in Berkshire than it does in Penrith, corresponding with the difference in the time the grass begins to grow.

Whether this rise is due to the temperature itself or to the flush of grass is a difficult point to decide. Plumb⁽²⁰⁾, Richards and Jordan⁽²¹⁾, and Davis⁽²²⁾, who kept cows at different temperatures, found that at higher temperatures a slightly larger yield was obtained; but Speir⁽²³⁾ could find no difference in the yield of cows kept at temperatures differing from 41 to 53° F. Kirsten⁽²⁴⁾, however, found that bad weather caused a decrease in yield.

Since, however, the average temperature usually increases from May to August and the daily yield shows a decline during this time, it would

appear that temperature is not the main cause of the monthly variation in daily yields. As the increase coincides with the turning out to grass in the spring it is probable that this is the main cause and there is abundant evidence for this view. Jones⁽²⁷⁾, Murray⁽²⁸⁾, Brunovsky⁽²⁹⁾, and Hopkins⁽³⁰⁾ have all produced direct evidence that fresh grass causes increased yield; this is so even when the concentrated foods fed in stall feeding have been more than sufficient to supply the needs of the animal. It is, however, necessary for the grass to be in a young, actively growing state, for it will be seen that in July and August when the cows are still at grass the yield declines. Various explanations have been put forward to account for this fact, and these may be grouped, for purposes of convenience, under four headings:

- (1) water content;
- (2) amino-acid content;
- (3) specific stimulating action;
- (4) action on calcium metabolism.

(1) A cow in milk requires a large supply of water but there is no evidence that increase of water intake will increase the quantity of milk. Larsen *et al.*⁽³¹⁾ found that by limiting the water supply a reduction in yield was produced, but Walker⁽³²⁾, Tangl and Zaitschek⁽³³⁾, Koch⁽³⁴⁾, and Berry⁽³⁵⁾, found that an increased water intake did not increase the yield: it must be concluded that the additional water in young grass is not the cause of the increased yield. Berry found, however, that if the water was given in the form of warm mashes, the yield was raised, which he attributed to its laxative effects; and similar effects occur with young grass.

It is known that the protein present in a young plant is more digestible than in an old one, owing to the additional amount of fibre present in the latter, and it may be that the fact of giving wet food renders the protein more easily digestible.

(2) Pfeiffer *et al.*⁽³⁶⁾ found that asparagin, an amide in which young grass is rich, increased the yield of milk independently of its nutritive value, and Morgen *et al.*⁽³⁷⁾ have obtained similar results. Bryner Jones⁽³⁸⁾ found that brewers' grains, and Henderson⁽³⁹⁾ that malt extract, markedly increased the flow of milk, these substances being rich in amino-acids.

(3) Fingerling⁽⁴⁰⁾ and Hansen *et al.*⁽⁴¹⁾ have attributed to certain foods a stimulating effect on milk secretion independent of their nutritive value, basing their experiments on the addition of these substances to a ration from which the aromatic substances had been removed.

(4) Recent work on rickets has shown that vitamins are intimately concerned with the calcium metabolism of the animal and Hart *et al.* (42) have found that something is present in green plant tissues, which affects the calcium metabolism, the limitation of which affects milk secretion. The relation of calcium and phosphorus in the blood to milk secretion has been studied by Meigs *et al.* (43). Hays and Thomas (44) found that the direct addition of calcium to the ration caused increased secretion. The cause of reduced milk flow of cows on heat has been attributed by Blair Bell (45) to derangement of the calcium metabolism.

It is possible, as a theory of milk secretion, that in the cells of the mammary gland, calcium unites with a glyco-phosphoprotein to form a calcium phosphoprotein (casein) and lactose, and that the stimulating effect of young grass is due, in part, to the action of vitamins affecting the calcium metabolism of the body.

A practical conclusion to be obtained from these results, is that the provision of food similar to young grass, such as young growing thousand-headed kale, young growing vetches, and perhaps silage, at times of the year other than that at which young grass is normally produced, would materially increase the amount of milk obtained from cows.

Maximum daily yield (p. 86).

The facts elucidated have a bearing on the question of the reliability of the 7-day test as used in the United States for estimating a cow's yield (46), investigations of which have been made by Woll (47) and Yapp (48).

Although it has been shown above that the maximum yield is an unreliable method of estimating the total yield, yet it does not necessarily follow that it is a worse method than the total yield, of estimating the genetic value of a cow for milk production (if due allowance is made for the time of the year), for, as has been shown, the effect of food, and date of service, cause considerable variation in the latter stages of lactation. It would appear that the amount of milk yielded by a cow depends on three main sets of factors.

(1) *The area of the gland available for production*, which is affected by the breed, age (largely), period of lactation, pregnancy (largely) and thoroughness of milking.

(2) *The supply of circulating nutrients available in the blood*, which is affected by food, dry period, pregnancy (slightly) and age (slightly).

(3) *Removal of the products of secretion*, which is affected by thoroughness and frequency of milking.

The first which is mainly genetic is often limited in its expression by the second which is nutritional, and the forcing of cows for heavy yields by high feeding enables a breeder to pick out those animals which have the genetic capacity to respond to the treatment. It is suggested that this may be more economically done by using the maximum yield than the total lactation yield as a basis for selection.

This, however, should not be allowed to detract from the value of yearly records in commercial herds, where feeding and conditions of management have to be studied.

If the maximum yield is used as a basis for selection, it is essential for comparative results that the cows compared should be milked the same number of times per day and at the same intervals for the pressure of milk within the udder is a potent factor in affecting the rate of secretion at the time of maximum flow.

Where high yielding cows are only milked twice a day the third factor mentioned above may become of genetic importance, as increase in the capacity of the cistern would allow secretion to proceed at a faster rate. Pliability and extensibility of the skin of the udder would produce the same effect in reducing the pressure of the products of secretion within the udder.

Whether the maximum daily yield is a true criterion of the genetic value of the cow for milk production, cannot be decided until it is known if the shape of the lactation curve is a genetic factor or if it is merely due to environment.

(B) Effect of Service (pp. 86-94).

The results obtained in this paper are in general agreement with those of Gavin⁽⁴⁹⁾ who found that service caused a drop in yield about the 16th-20th weeks of pregnancy. The origin of the inhibition of secretion at this time is at present under investigation, and is believed to be due to growth changes arising as the result of an internal secretion from the reproductive organs; physiologists who have studied the action of injected extracts are not agreed, for Lederer and Pribram⁽⁵⁰⁾ found that extract of placenta augmented milk secretion, while Mackenzie⁽⁵¹⁾ found that both foetus and placenta extract inhibited it¹. Palmer and Eckles⁽⁵²⁾ found that the same changes in the composition of milk occurred at the end of a barren lactation as at the end of a pregnant one, but at a later stage. They consider that the hastening of the close of lactation is the

¹ For further references see Marshall, *The Physiology of Reproduction* (new edition), London, 1922.

important factor involved in the changes in the composition of milk as the lactation advances and that the changes are much more marked in low than in heavy producing cows⁽⁵³⁾.

Practical men believe that the extent to which pregnancy influences the yield is affected by breed differences, a high producing strain showing less diminution in yield¹.

(C) Age (pp. 94-98).

Several other investigators have worked on the corrections to be made for age. The majority of these, however, have failed to distinguish between age itself and the factors which are coincident with it, such as the elimination of bad cows, and the variations in service period with age. For this reason our results do not agree with the majority of those of other investigators; which mode of correction should be used will depend on the object in view. The results obtained by other workers are shown in Table D, calculated to the basis of yield at 1st calf = 100.

The expression "lumped lactations" has been used for records compiled from masses as distinct from those for individuals.

A comparison of these figures brings out several facts which have to be considered when dealing with age changes in yield.

(a) Results based on maximum daily yields, whether as such, or as show ring yields or 7-day tests, show greater differences between first and maximum yields than those based on lactation periods, due in all probability to the reduced daily yield of 1st calvers. The Danish figures, however, are exceptional and may be due to local conditions, such as early calving and milking three times a day.

(b) Results obtained from "lumped" lactations show the ages of maximum yield to be higher than those based on successive yields of the same cows. This is due to the weeding out of bad cows, although Gowen, who obtained an early maximum for Jerseys, found that selection did not operate in the pedigree herd investigated.

(c) Results based on maximum daily yields are not dependent on the service period, but neglect of this factor makes the results based on total lactations variable; these variations tend to increase the longer the

¹ Wilson⁽⁷⁰⁾ has recently published data bearing on this point but unfortunately his paper was not obtained soon enough for inclusion in the above discussion. His results for Ayrshires as compared with ours on Shorthorns show the following differences in lactation yield:

S.P. (days) ...	49	84	112	147	175
Wilson	100	103.1	106.2	108.6	112.7 .
Present paper ...	100	109.5	116.4	124.1	128.6 .

Table D. *Comparative yields at different lactations calculated from various authors (1st lactation = 100).*

Authority	Breed	Average yield with 1st calf	Notes	Method of estimation	Comparative yields																
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Gavrilov	Shorthorns and Friesians	24.5	Revised maximum daily yield	Successive yields of same cows	100.0	130.6	146.9	156.1	161.2	163.3	161.2	161.2	—	—	—	—	—	—	—	—	—
Wilkinson	Large breeds	39.3	Daily yield London Dairy Show 3 years=1st calf	Lumped lactations	100.0	119.6	130.8	140.5	144.8	147.6	137.9	144.8	152.9	—	—	—	—	—	—	—	—
Holldaynes	Friesian	45.3	Daily yield 7 day tests (U.S.A.) 2 years=1st calf	Lumped lactations	100.0	121.1	137.9	144.9	149.5	149.6	149.8	149.8	146.1	146.6	—	—	—	—	—	—	—
Pearl and Miners	Ayrshire	19.8	Mean daily yield throughout lactation (3 years=1st calf)	Lumped lactations	100.0	110.0	118.9	126.2	130.4	131.9	134.1	133.8	134.5	134.4	133.8	132.5	130.7	128.3	—	—	—
Tochem	Ayrshire	52.46	Similar material to above (2 years=1st calf)	Lumped lactations	100.0	106.5	116.0	122.4	127.8	132.3	135.6	138.0	139.4	139.7	138.9	137.3	134.5	130.8	126.0	120.2	113.4
Bartlett	Crossbred Shorthorn	63.86	"Lactation yearly yield"	Successive yields of same cows	100.0	106.7	116.0	114.0	—	—	—	—	—	—	—	—	—	—	—	—	—
Gowen	Jersey	40.33	8 months' yield 2 years=1st calf	Lumped lactations	100.0	116.2	123.8	131.0	137.3	131.7	129.6	122.4	120.0	—	—	—	—	—	—	—	—
Pearl and Patterson	Jersey	30.1	Mean daily yield 7 day tests (U.S.A.)	Lumped lactations	100.0	111.4	115.7	117.2	119.0	120.1	119.4	120.3	121.2	117.3	115.8	121.5	107.1	—	—	—	—
Eckhart	Jersey (mostly)	48.18	2 years=1st calf	Successive yields of same cows	100.0	112.4	124.4	132.6	131.3	133.8	132.1	—	—	—	—	—	—	—	—	—	—
Gowen	Friesian	140.19	2 years=1st calf	Lumped lactations	100.0	112.3	119.5	127.3	133.5	135.2	135.4	135.8	123.8	141.5	118.6	103.4	—	—	—	—	—
Langmack	Angler *	56.94	Record for 400 days	Successive yields of same cows	100.0	114.7	132.1	146.4	148.5	160.1	150.5	151.6	143.4	133.0	—	—	—	—	—	—	—
Langmack	Fynsk *	53.60	" "		100.0	113.0	131.8	141.4	152.5	152.8	157.2	156.7	155.8	149.4	—	—	—	—	—	—	—
Langmack	Jutland	53.88	" "		100.0	115.3	136.4	142.5	154.3	152.6	159.4	149.9	154.6	154.5	—	—	—	—	—	—	—
Present paper	Crossbred Shorthorn	49.00	Lactation records		100.0	110.5	122.3	122.5	130.3	—	—	—	—	—	—	—	—	—	—	—	—

* Red Danish.

limit fixed, in selecting data, for the duration of the lactation. This is probably one of the reasons why Langmack's results showed a later maximum than our own. Bartlett eliminated service effect by his method and obtained an early maximum age; neglect of the service period, would, as a rule, tend to increase the age of maximum production; it would appear that by his method an over-correction for service period is effected, by applying linear corrections for what is apparently a logarithmic function.

(d) Results will also depend on the age at which the first calf is produced; in compiling the above table this has been taken as between 2-3 years (U.S. Dept. Agr. Statistics⁽⁵⁴⁾ have shown it to be $2\frac{1}{2}$ years), but this will normally vary with breed and local conditions. The evidence adduced by Eckles⁽⁵⁵⁾ and Towles⁽⁵⁶⁾ would seem to indicate that early calving results in a reduced yield for the first lactation, which would tend to raise the maximum lactation yield as compared with the first. That heifers having high yields with their first calves tend to reach their maxima earlier than heifers having a low first calf yield is suggested by the details of Eckles⁽⁵⁷⁾ results, and has been found to hold in the case of very low yielders by Bartlett.

(e) Heavy feeding will also tend to lower the maximum yield compared with the first lactation yield, more especially in respect to the maximum daily yield, the effect on young animals being greater owing to their coincident growth. For this reason Wilson's figures for show animals are below those of Gavin for commercial stock.

(f) Breed differences are shown to a certain extent in Langmack's results on three Danish breeds all calculated in the same way, and are indicated by the results of other investigators. They are in practice, however, obliterated, to a certain extent, by alterations in the age of first calving.

(D) Dry Period (pp. 98-102).

Little accurate research has been done on the effect of the dry period in influencing the amount of milk secreted, although it has been realised by practical men that a cow milks better after a rest.

As has been pointed out above the normal period of rest before calving varies with the circumstances of farming, whether high or low feeding, or spring or autumn calving, is adopted. In the present investigation the average period of 85 days is above that of about 60 days found by Gavin, and that of 56 days found by Pearl⁽⁵²⁾ in America. No data are at present available to show how far the natural length of the dry

period is an individual or breed characteristic, although there is a wide belief to this effect in practice.

The facts obtained in this paper are in general agreement with those obtained by Gavin⁽¹⁰⁾ who found a reduced maximum daily yield for cows dry less than 35 days, but he found no difference for cows dry longer than this period. Carroll⁽⁶³⁾ found that cows dry 60 days produced more than cows dry only 30 days, and a longer rest gives no more increase.

Two possibilities exist as to the effect of the dry period on the cow:

(a) A rest may be necessary for complete growth during the anabolic phase of the udder brought about by pregnancy.

(b) A rest may allow the body to accumulate a store of nutritive material, on which the mammary gland may draw at the time of maximum daily yield, when the food intake is very often insufficient to supply both the maintenance, and milk production, requirements of the animal.

There is little evidence to support (a); it has undoubtedly been shown that the anabolic phase of growth proceeds, at the twentieth week after service, at the expense of milk production, but there was some evidence of a rise of yield associated with dry periods of over 120 days, that is, if the cow was dry before the growth phase of the mammary gland (20 weeks after service) began. Dry periods of between 40 and 120 days have, however, only a small effect on the subsequent yield, and it would seem possible that most of the mammary growth could be effected by a dry period of approximately 40 days; dry periods of less than this time causing markedly reduced yields.

In support of (b) Haecker⁽⁹⁾ has shown that cows lose weight during the early stages of lactation and Eckles⁽⁶⁴⁾ that this depends on the plane of nutrition of the cow. Only a small amount of evidence is available as to the nature of this storage material. Hammond and Hawke⁽⁶⁵⁾ have shown that temporary defective nutrition raises the fat percentage of the milk by reducing the total amount secreted, and Eckles that the fat percentage of milk varies with the state of nutrition of the cow before calving, provided she is underfed after it; from which it would appear that the storage of fat is not responsible for the yields made after a dry period, although the fat percentage of the milk might be affected thereby. Moreover it has been shown that although a cow's yield is considerably lowered by a very short dry period, it is not greatly increased by a very long one, which would point to a limitation in storage capacity for this material—such is not the case with fat.

Hart, Humphrey and Schaal⁽⁶⁶⁾ have shown that in cows, during their period of maximum yield, milk secretion takes place on a negative

nitrogen basis, the flow being maintained in spite of the loss of nitrogen from the body; so that the animal uses its own body proteins to produce milk. Ellett and Holdaway⁽⁶⁷⁾ found that a cow in the early stage of lactation, if underfed in protein, loses flesh rapidly and her milk flow then decreases until she is able to maintain the flow on her intake. Mellanby⁽⁶⁸⁾ concluded that the creatine excreted in the urine bears a definite relation to the activity of the mammary gland; this would appear to be evidence that protein may be the main factor involved.

The relation between vitamins and the supposed calcium action with the glyco-phosphoprotein of the mammary glands (see under "Month of calving" in this section) would, in the present state of knowledge, make it uncertain whether the necessary storage material was the protein itself, or the vitamin which renders it available for milk secretion.

It is to be expected, therefore, that the effect of the dry period in influencing the total lactation, and to a greater extent the maximum daily yield, will depend on the plane of feeding adopted after calving, the better the feeding after calving the lesser being the effect the dry period will have. It would also be expected that the poorer the condition of the cow the greater would be the effect of the dry period in increasing yield, and that the effect would be greater in very young (with coincident growth) and in very old (with coincident senility) cows, than in cows at their prime; for, as shown in Fig. 15 above, storage of material made in the dry period is used after calving both for milk production and for reproduction; for if the dry period is long (say over 100 days) the reserve material present is sufficient to support reproduction at about the time of the maximum yield. If the dry period is reduced, however, below (apparently) 40 days the anabolic phase of growth in the mammary gland, building it up for the succeeding lactation, is affected and less milk is produced—more especially at the period of maximum yield (Gavin⁽¹⁰⁾); this reduced maximum yield of cows having a dry period of less than 40 days appears to be caused by "developmental" rather than nutritional causes.

SUMMARY.

(1) The variation of the total yields according to the month of calving is given, and causes for this variation are suggested from the mean lactation curves of cows calving in each month.

(2) A curve showing the effect of pregnancy on the lactation yield has been prepared and corrections are given for different lengths of service

periods after calving—"100 days" being chosen as a standard, as that was found to be the average of all service periods obtained, and as it gives a calf at about the same time in the following year.

(3) The variation in yield as the cow gets older has been studied and corrections are given. The maximum yield appears to be reached at the fifth calf; it was found that service periods varied in a definite way with age.

(4) The effect of the dry period before calving on the subsequent yield is shown; "85 days" has been taken as a standard and corrections given accordingly; the standard was the mean of all dry periods obtained, but is probably above the average throughout the country.

(5) By applying these corrections, the variation of individual totals is reduced by approximately 20 per cent. and the number of lactations showing less than 5 per cent. variation is increased by 27.3 per cent.

(6) A brief review of other literature on the subject is given, and the results obtained in this paper are compared with those of other investigators.

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SOME FACTORS AFFECTING THE EVAPORATION OF WATER FROM SOIL.

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IN 1914 the result of a study of the evaporation of water from soil was published by B. A. Keen¹, who distinguished two factors governing the rate of evaporation. One factor was that the available surface from which evaporation takes place decreases as the moisture content decreases. Keen deduced an equation that expressed the operation of this factor, viz.

$$-\frac{dw}{dt} = D \sqrt[3]{\left(\frac{ws}{100} + 1\right)},$$

in which D is a constant, w = percentage of water by weight and s = the real specific gravity of the soil. He showed that this equation agreed with his experimental results with a reasonable degree of accuracy.

The other factor was the vapour pressure of the water in the moist soil. It is obvious that, other things being equal, the rate of evaporation of water at any instant from soil in dry air or indeed from any material colloidal or crystalloidal, must be directly proportional to the vapour pressure². During evaporation the moisture content of the soil is continually diminishing and therefore the vapour pressure falls off. That is, the driving force producing vaporisation of the soil water becomes less and less as the drying proceeds and thus the rate of evaporation decreases also. As Keen pointed out the complete explanation of this factor demands a knowledge of the relation between vapour pressure and water content and this at that time was quite unknown in the case of the system soil—soil moisture. The factor however could be expressed with a considerable degree of accuracy by the empirical expression

$$A \frac{dw}{dt} = 2.303 \log_{10} (w + k) - \log_e K,$$

in which A and K are constants.

¹ *Journ. Agric. Sci.* 6 (1914), 456–75.

² Really $-\frac{dw}{dt} = k(p_1 - p_2)$ where p_1 = v.p. of the evaporating liquid and p_2 = the partial v.p. of that liquid in the atmosphere. This obviously reduces to $-\frac{dw}{dt} = kp_1$ when the drying atmosphere is of zero humidity.

By combining these two expressions Keen obtained

$$B \frac{dw}{dt} = \sqrt{\left(\frac{ws}{100} + 1\right)} [2.303 \log_{10}(w + k) - \log_e K].$$

This expression was found to fit the rate curves obtained down to a moisture content of about 3 %. At this point the observed and calculated curves began to diverge. The calculated curve was entirely concave to the horizontal axis as any curve expressible by an exponential type of equation would be expected to be while the experimental curve became convex to the axis of abscissae near the origin with a point of inflexion at about $w = 1.5$ %. As Keen rightly pointed out, at this region of very low water contents some divergence between the experimental and observed curves is not surprising "even if only that due to experimental irregularities." He consequently assumed that his equation completely defines the rate curves over the whole range of his experiments. Comparison with the results obtained with ignited garden soil showed how wide was the difference in evaporation from the two materials and evidence was adduced to show that the differences are bound up with the colloid properties of clay.

In view of the accuracy of the experimental method employed it does not seem probable that the divergence of the two curves below 3 % water content can be due entirely to experimental error and this is supported by the fact that the divergence disappeared and the change in curvature became practically inappreciable when the soil sample was dried over 55.4 % H_2SO_4 , i.e. in an atmosphere in which the aqueous tension is 6.3 mm. Under these conditions the soil is in equilibrium with the drying atmosphere when it has about 3 % of moisture left in it. The discrepancy therefore seems to indicate that Keen's final equation is not a complete expression for the relation between vapour pressure and moisture content and that the true curve really is of a more complex type with possibly a point of inflexion in it. Evidence in favour of this view was obtained by the writer in the course of a study of the rate of evaporation of moisture from textile and other colloid materials using Keen's experimental method. Search in the literature also afforded further evidence for this view and the whole problem has been reinvestigated in the writer's laboratory.

Regain curves in the case of textile materials have been determined with considerable accuracy by Schloessing¹ in France and by Hartshorne²

¹ *Text. World Record*, 36 (1908), 219-26.

² *Trans. Amer. Soc. Mech. Eng.* 30 (1918), 1073-1128.

in America. "Regain" of textile materials is the term applied in the industry to the percentage moisture content (calculated on a dry weight basis) that is in equilibrium with an atmosphere of any given temperature and relative humidity. By plotting percentage moisture contents as abscissae and relative humidities as ordinates we get what is essentially a vapour pressure curve. Orme Masson and Richards¹ have also worked

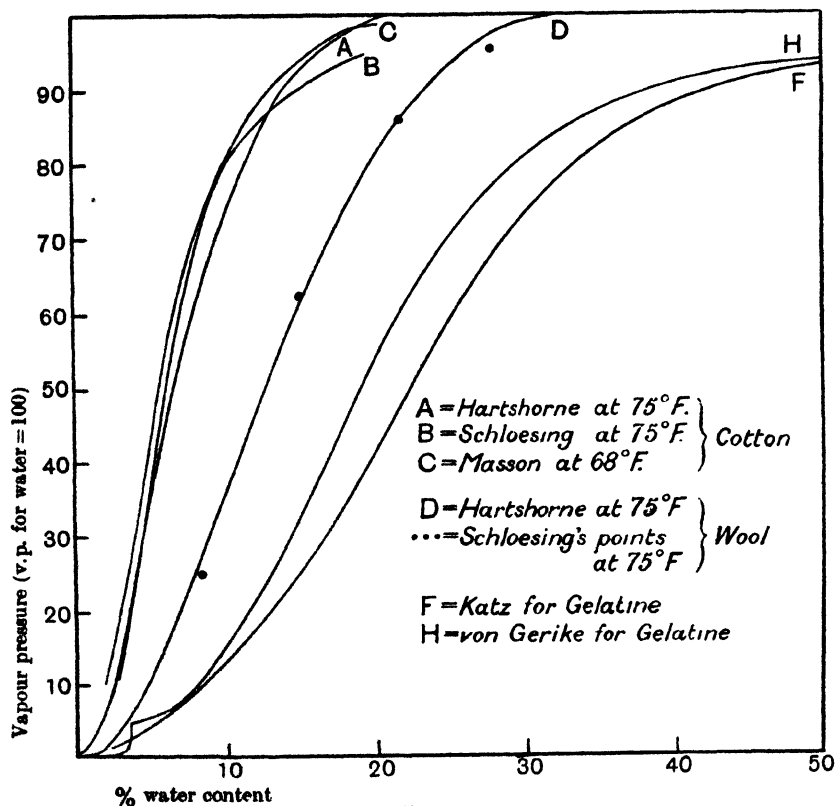


Fig. 1.

out a vapour pressure curve for cotton. In Fig. 1 are given the regain curves for wool and for cotton obtained by these different investigators so that an idea of the general type and accuracy attained may be gathered. The vapour pressure curves of gelatin obtained by Katz² and by Von Gerike³ are also given for comparison. The latter serve to show

¹ *Proc. Roy. Soc.* **73** (A) (1906), 412-29.

² *Zeit. f. Elektrochem.* **17** (1911), 800-805; *Koll. Chem. Beihefte*, **9** (1917-18), 1-182.

³ *Koll. Zeit.* **17** (1915), 78-104.

that gelatin also conforms to the general type of curve. It is probable that the vapour pressure curve of all colloid materials is of this general sigmoid type—the sigmoidness being very pronounced in contrast to the very slight sigmoidness of the soil rate of evaporation and vapour pressure curves. The vapour pressure curve for a clay soil shown in Fig. 2, Curve A, is from Thomas¹; it differs considerably from the other curves and from the rate curves of Keen, but a point of inflexion near the origin is indicated.

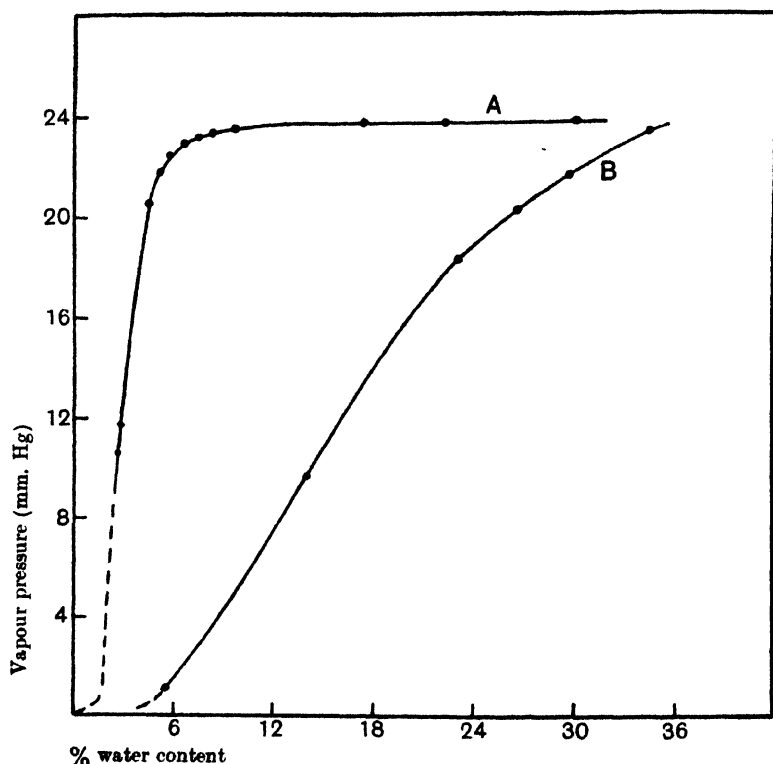


Fig. 2.

The very inconspicuous sigmoidness of the soil curves is in striking contrast to that of the other cases considered and casts an interesting sidelight on the physical nature of the soil complex. Wool, cotton, gelatin, etc., are typical colloid materials and when in equilibrium with aqueous vapour the concentration of moisture is similar throughout the mass. The soil however is not a typical colloid. It is to be regarded

¹ *Soil Sci.* 11 (1921), 409-34.

rather (in its physical aspect, the only one we are concerned with here) as a collection of relatively non-hygroscopic non-colloidal particles of irregular and variable shapes and sizes with a gelatinous or colloidal coating. It is with this colloidal coating that the soil water is considered to be mainly associated and the mineral framework may be regarded

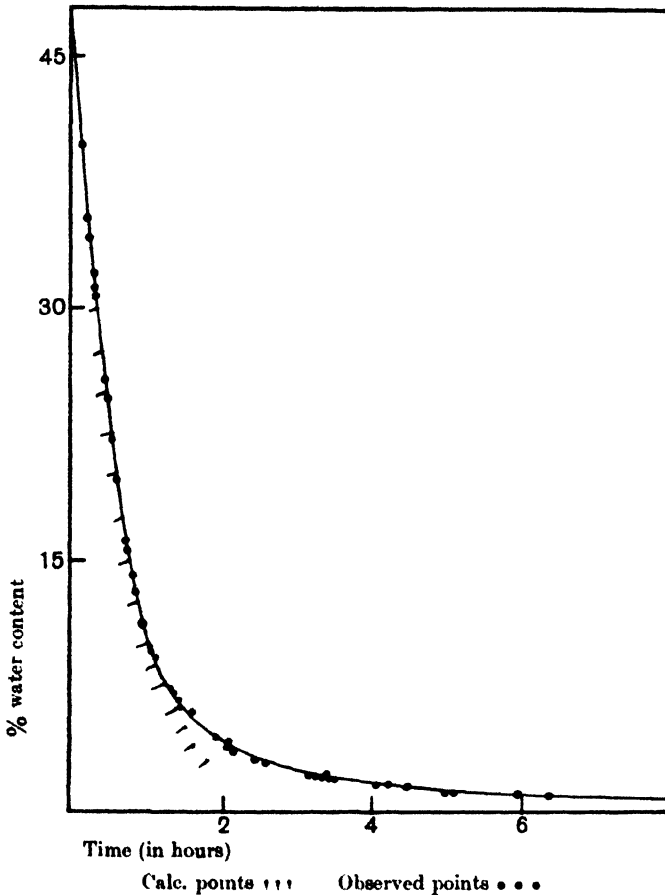


Fig. 3.

from this point of view as hardly more than a diluent. If we were to calculate the moisture content not as a percentage on the total weight of dry soil but rather on the total weight of dry soil-colloid it is easy to see that the effect of this would be to shift the point of inflexion very much further to the right which would make the curve similar in character to those for wool and gelatin.

In Fig. 3 is given a curve, based on data obtained by the writer showing the variation in moisture content of a woollen fabric with time of drying, and the rates of evaporation obtained graphically from this curve plotted against the moisture contents are shown in Fig. 4 (Curve A), while drawn on the same scale is Hartshorne's latest regain curve for the same material (Curve B). The two latter curves show wide

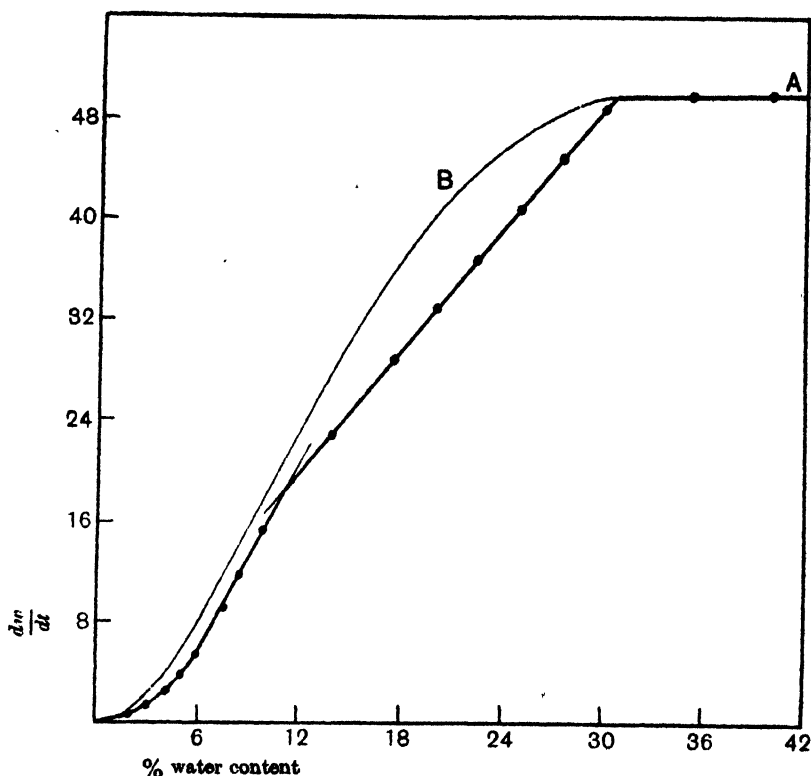


Fig. 4.

divergences, the vapour pressure curve being sigmoid and continuous while the rate of evaporation curve is made up of four distinct and separate portions, three of which are straight lines, and there are three points on the curve at which there are sudden changes of direction. There are evidently other factors at work that determine the shape of the rate curves in the case of colloid materials besides the two dealt with by Keen. These have been investigated by the writer and are discussed in detail elsewhere¹. They will be discussed here briefly in so far as they

¹ *Roy Soc. Proc.* 95 (A) (1923).

bear on the question of soil moisture. Along the first, straight, horizontal portion of the rate curve, i.e. down to 31 % water content, the rate of evaporation is constant, i.e. $-\frac{dw}{dt} = k_1$. Here evaporation is taking place from a free-water surface and we are merely getting rid of the mechanically adhering water. At 31 % water a sudden change in direction occurs and along the portion 31 % to 11 % water the curve is straight and on extrapolation would pass through the origin. Along this portion of the curve the rate of evaporation falls off steadily and is directly proportional to the water content, i.e. $-\frac{dw}{dt} = k_2w$. Obviously other factors besides the falling off of vapour pressure are operative here as the vapour pressure curve and the rate curve are not identical. One factor is due to temperature. The temperature of the drying mass is variable and increases steadily from the "wet" end of the curve towards the dry. It is obvious that a mass of moist material kept in a dry atmosphere is under conditions roughly comparable to those of a wet bulb thermometer. Under the particular conditions dealt with here the temperature of a wet bulb thermometer should fall rapidly to about 9° C. since the wet bulb depression for the relative humidity zero and temperature 25° C. is 16.5°. On account of the considerable radiation that takes place inwards from the walls of the drying vessel and the transfer of heat to the drying mass by conduction and convection the full wet bulb depression is never registered in the case of soil or other mass of drying material, although a considerable depression of temperature must occur; in the case of a small vessel of water evaporating under these experimental conditions the writer detected a fall of temperature of 7° C., i.e. about half the wet bulb depression. At first, therefore, the rate of evaporation is very much slower than it would be if there were no fall in temperature. As the material begins to dry out and the rate of evaporation to fall off in consequence the temperature gradually rises until it finally reaches 25° C. The progressive lowering of the rate of evaporation is therefore less than it otherwise would be and the vapour pressure curve higher and flatter. That this factor is of importance is seen at once by a reference to tables of the vapour pressure of water at different temperatures. At 18° C. the vapour pressure is 15.4 mm. of mercury while at 25° C. it is 23.5 mm. Since, other things being equal, the driving force of evaporation is the vapour tension of the soil moisture and assuming that, at the start, the material is so moist that we are dealing with a free water surface then the observed rate of

evaporation at the start (i.e. at 18° C.) is to the calculated rate at the start (i.e. at 25° C.), as 15.4 is to 23.5. An examination of the evaporation (*A*) and vapour pressure (*B*) curves of Fig. 4 reveals however that this factor must increase the divergence of the two curves; the rise of temperature increases the vapour pressure and therefore the actual vapour pressure curve will be above the one shown in the figure throughout almost its whole length. The cause of the divergence of the two curves must therefore be sought for in some other factor or factors that contribute towards the rate of evaporation. At 11 to 10 % water content a second sudden change of direction occurs and along the portion from 10 % to 5 % water, the rate curve is still straight but on extrapolation would cut off an intercept *c* from the horizontal axis. Along this portion the rate of evaporation can be expressed by $-\frac{dw}{dt} = k_3(w - c)$. At point 11 % water a further factor operates which in the absence of more precise knowledge may be provisionally described, in soil at any rate, as due to capillarity. At all points of the curve the actual thin surface layer dries very rapidly and the loss has to be made good by a movement of water from the interior. This movement is brought about in the case of soils by capillarity as discussed in a very thorough manner by Briggs¹, and especially by Buckingham², and by Gardner³, although they did not take into account the colloid nature of the surface they were dealing with. The drier a soil is the slower will this capillary "rise" be and at some stage or other of the drying process the rate of this capillary rise will become equal to the rate of surface evaporation and from that point onwards will act as a limiting factor to the rate of evaporation. From this it follows that the law connecting rate of evaporation (at constant temperature) with vapour pressure holds strictly only for the actual surface layer since Buckingham² showed that no evaporation occurred from the interior of the soil. In general we may say that a thermodynamic potential due to the capillary nature of the system⁴ must exist between the interior and the surface of the drying mass which results in a movement of the water towards the surface as the latter dries out. Below 11 % water in the case of wool the rate of this movement becomes slower than the rate of surface evaporation and the latter in consequence becomes independent of the vapour pressure and is determined almost solely by the rate of movement of the internal water.

¹ *U.S. Bureau of Soils, Bul. 10* (1897).

² *Ibid. Bul. 38.*

³ *Soil Sci. 10* (1920), 103-26; **11** (1921), 215-32.

⁴ Buckingham, *loc. cit.*; W. Gardner, *loc. cit.*

This capillary explanation also renders explicable the divergence between the vapour pressure and evaporation curves in the case of wool between 31 % and 11 % water and in the corresponding portions of the soil curves. Thus if there are present a series of pores of radii $r_1 > r_2 > r_3 > \dots r_n$ and the numbers of such are $n_1, n_2, n_3, \dots n_n$, then the areas of cross section of these various groups are $\pi n_1 r_1^2, \pi n_2 r_2^2, \pi n_3 r_3^2, \dots \pi n_n r_n^2$. These areas are evaporating water at different rates and the larger r is the larger the rate. The rate, however, at which the pores will become empty will obviously depend on the ratio of the rate of evaporation (which is dependent on the vapour pressure, p_1 , at the meniscus—and which is a logarithmic function of r —and on the linear dimensions of the surface, i.e. directly on r) to the volume of water to be evaporated (which depends, for a given length of pore, on r^2). This ratio is not constant for different values of w and therefore the above areas will become “dry” at different rates, one area becoming “dry” before another and so on. In consequence the effective evaporating surface will progressively diminish, and the rate of evaporation falls rapidly in consequence.

Below 5 % water content in the case of wool the rate curve bends round to the origin, the evaporation becoming very slow. It is inferred that it is along this region that the really hygroscopic or adsorbed water or water that may perhaps be held chemically is given off.

From the above equations the rates of evaporation, i.e. the tangents to the experimental curve, can of course be calculated if we know the values of the constants k_1, k_2 , and k_3 . Thus along the first sloping portion we get $-\frac{dw}{dt} = k_1 w$ or $-\frac{dw}{w \cdot dt} = k_1$. By dividing each tangent obtained graphically over this region by the corresponding value of w we get values for k_1 . These are not as a rule identical owing to the not inconsiderable error involved in measuring tangents graphically, but by taking the mean value of k_1 so found we can calculate the values of the various tangents. These calculated values agree fairly well with the observed ones and in fact when checked by means of a straightedge against the experimental time curves from which the rate curve has been derived are found to fit this curve quite as well as the observed values. It is important that the tangents should be calculated in this way as the portion of the rate curve considered when found by the graphical method alone does not as a rule point exactly to the origin but generally above it, and this calculation affords a simple method of eliminating the errors due to the graphical method. A stricter check is to integrate the above

equations and to calculate times. Thus if $-\frac{dw}{dt} = k_2 w$ is the equation representing the portion of the rate curve between 31 % and 11 % water the integrated form of this, i.e. $\log k_2 w = -k_2 t + C$, is the equation of that portion of the experimental time curve from which the rate curve has been derived. We therefore have $\log \frac{w_1}{w_2} = k_2 t$ in which w_1 and w_2 are any two values of w between 31 % and 11 % (Fig. 3), and t is the time taken for the moisture content of the sample to be reduced from w_1 to w_2 . By taking two extreme values for w_1 and w_2 , t for these values being read off from the curve, it is easy to calculate the value of k_2 and by using this value, the value of t for all intermediate values of w can be calculated. This has been done and in Fig. 3 are given both the calculated and the observed points on the experimental time curve for wool. This curve is the mean curve of six series and it will be noticed how accurately the calculated points fit this smooth curve and how they fall away from it in the portion below $w = 11$ % where the equation ceases to apply. This affords a rigid proof that the portion of the rate curve considered does point to the origin and is completely expressed by the equation given.

The rate curve for wool has been examined in some detail as it is the simplest curve so far obtained and the changes of direction are very sharp and pronounced; it leads up to the more complicated types met with in the case of soils.

The first soil examined was a heavy Rothamsted subsoil kindly supplied to the writer by Sir John Russell. Its mechanical analysis was as follows:

	%		%
Moisture	13.6	Fine Sand	0.9
Loss on Ignition		Silt	1.9
(less moisture) ...	13.6	Fine Silt (1) ...	2.4
Fine Gravel	0.7	Fine Silt (2) ...	4.4
Coarse Sand	0.4	Clay	55.4

The rate curve (corrected) obtained for this soil is given in Fig. 5 (Curve A). At first sight there appears to be little resemblance between this curve and the corresponding one for wool while it does not appear to be very dissimilar from the one obtained by Keen for Hoos field (also shown in Fig. 5, curve B). Mathematical analysis however reveals the essential characteristics of the curve and reveals its discontinuous nature. Along the straight horizontal portion at the "wet" end of the curve we have evaporation taking place from a free-water surface the rate of which is expressible by the equation $-\frac{dw}{dt} = k_1$. At about 35 % water

content a sharp change of direction occurs, the rate of evaporation falling off rapidly. The portion of the curve xy , however, unlike the corresponding portion of the wool curve, shows considerable curvature although it will be noticed that on extrapolation it would pass through the origin. Evidently along this portion of the curve a further factor is at work in addition to those operative in the case of wool. This factor is the considerable shrinkage that takes place as the soil dries out resulting presumably in a diminution in the evaporating surface as the evaporation

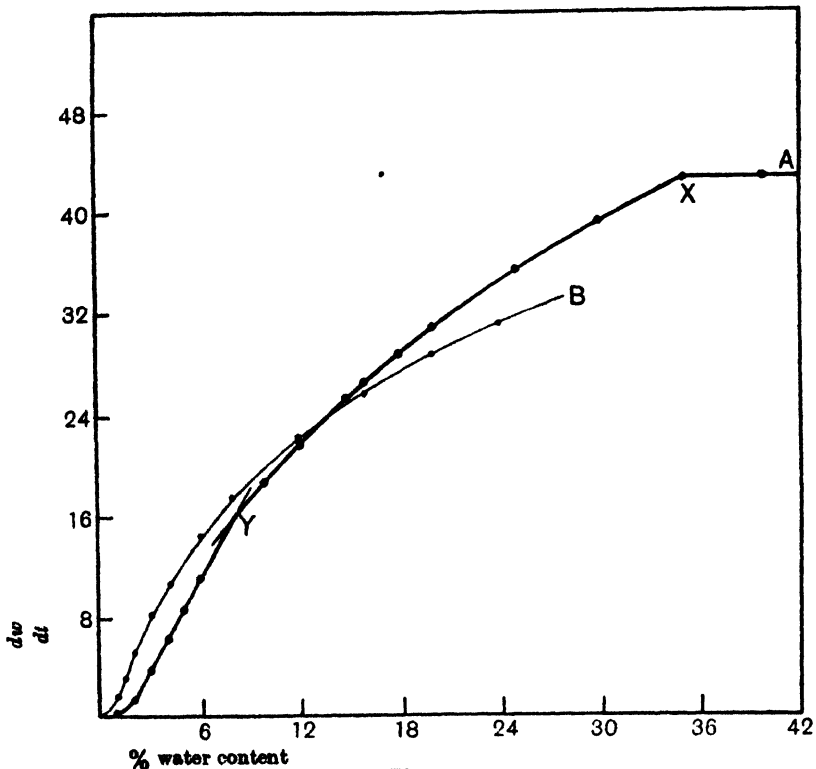


Fig. 5.

proceeds¹. Already at 60 % water content numerous fine cracks appeared throughout the soil mass. These increased in number and width, and eventually the soil separated into a large number of irregularly shaped

¹ [Note added Feb. 22nd, 1923. Since this was written the work has been extended in various directions and to other materials. The results indicate that the curvature in the evaporation curve for clay soil is not the simple shrinkage effect described above. This point will be discussed in detail in a later paper and may necessitate a modification in some respects of the point of view developed in this section.—E. A. F.]

"islands" which steadily diminished in area and thickness as the soil dried out¹. It is known that in large scale drying of materials such as glue, soap, etc., that shrink considerably in the process the thickness of a mass of material is proportional to its water content within a considerable range² and it suggests itself that a simple relationship may exist between water content and surface shrinkage. The shrinkage, however, ceases at a definite water content (= 7 % in this particular case) and the portion of the curve *xy* is expressible by the equation

$$-\frac{dw}{w \cdot dt} - a \frac{(w-7)}{w} \frac{dw}{dt} = k_2,$$

in which *a* and *k*₂ are constants. It will be seen from Table I, columns 2 and 3, that the observed and calculated tangents agree satisfactorily, but the rigid test is integrating the equation and calculating the time curve. Thus we get

$$2.303 (1 - 7a) \log \frac{w_1}{w_2} + a (w_1 - w_2) = k_2 t,$$

in which *a* and *k*₂ are constants equal (in this particular case) to 0.027 and 1.020 respectively. It will be seen from Table I, columns 4 and 5, how closely the observed and calculated times agree with one another over the portion of the curve to which the equation applies, i.e. between 35 % and 8 %. Now the rate of evaporation, other things being equal, is not proportional to the evaporating surface but to some power of the radius (when the surface is circular); to the first power according to the early work of Stefan and Winkelmann, but to some higher power between the first and second, depending on conditions

¹ The first weighings were taken at about 57 % water content after the first fine cracks had already appeared. Although these increased in number and width they produced no appreciable variation in the rate of evaporation as long as free water was evaporating. Thus the experimental time curve between 57 % and 35 % water showed no indication of curvature, the rate curve for this region being straight and horizontal. The rate of evaporation over this region, however, was not quite identical with that from the silty soil which showed no signs of cracking. Thus the silty soil lost 114 c.g. of water in 2.471 hours (in the region covered by the straight portion of the experimental time curve) as against 114.93 c.g. in the same time for quartz sand and 118.07 c.g. for the Rothamsted subsoil. The values should be identical in all three cases. The sand lost 0.815 % more water than the silt and this may be regarded probably as an indication of the order of magnitude of the experimental error inherent in the method. The Rothamsted subsoil lost 3.57 % too much water and the excess may be attributed to the slightly increased evaporating surface in this case due to the formation of the cracks.

² W. K. Lewis, *Journ. Ind. and Eng. Chem.* **13** (1921), 427-32; R. F. Geller, *Journ. Amer. Cer. Soc.* **4** (1921), 282-7.

according to the later experimental work of Burger¹ and of Thomas and Ferguson². It is however not unlikely that under the relatively constant drying conditions dealt with here the rate of evaporation is proportional to a constant power of the radius of the surface whatever that power may be. The effect of the shrinkage on the rate of evaporation is however proportional to an *increasing* power of the water content as the latter

Table I.

Comparison of observed and calculated results for evaporation of water from samples of deep Rothamsted subsoil (55.4 % clay).

w	$-\frac{dw}{dt}$ (obs.)	$-\frac{dw}{dt}$ (calc.)*	t in hrs (obs.)	t in hrs (calc.)†
40 %	42.70	—	—	—
30	39.72	38.00	1.073	1.066
25	36.80	34.40	1.335	1.335
20	30.76	30.20	1.64	1.64
18	28.24	28.30	—	—
16	26.22	26.10	—	—
15	24.78	25.20	2.00	1.997
12.5	—	—	2.21	2.208
12	21.50	21.50	—	—
10	18.50	18.90	2.46	2.46
9	—	—	2.57	2.567
8	15.60	15.90	2.695	2.690 [2.840]§
7	13.40	[12.966]‡	2.840	2.825 [3.007]§
6	11.11	[10.80]‡	3.00	2.980 [3.211]§
5	8.696	[8.64]‡	3.21	3.157 [3.474]§
4	6.78	[6.48]‡	3.47	3.370 [3.845]§
3	3.972	[4.32]‡	3.84.5	3.635 [4.479]§
2	1.70	—	4.690	—
1	0.34	—	6.780	—

* Calculated between 30 and 8 % water from $-\frac{dw}{w \cdot dt} - a \frac{(w-7)}{w} \frac{dw}{dt} = k_2$, in which $a=0.027$, $k_2=2.040$.

† Calculated from $2.303 (1-7a) \log \frac{w_1}{w_2} + a (w_1 - w_2) = k_2 t$, in which $a=0.027$, $k_2=1.020$.

‡ Below 8 % calculated from $-\frac{dw}{dt} = k_2 (w-c)$, in which $k_2=2.161$, $c=1$.

§ Calculated from $\log \frac{w_1 - c}{w_2 - c} = k_2' t$, in which $c=1.00$, $k_2'=0.4747$.

Note. The constants have different numerical values in the equations of rate and the corresponding integrated forms owing to the fact that, while different amounts of dry matter were used with the different soils, the rates have all been calculated to the same weight of dry matter to make the curves more comparable. This is legitimate as $-\frac{dw}{dt}$ has been found to be inversely proportional to the dry weight.

falls off: for the equation of rate indicates that the difference between the observed rate of evaporation $\left(-\frac{dw}{dt}\right)$ and what the rate would be if

¹ *Sci. Abs. (Physics)*, **22** (1919), 171.

² *Phil. Mag.* **34** (1917), 308-21.

there were no shrinkage is equal to $a(w - 7) \frac{dw}{dt}$, and $\frac{dw}{dt}$ is not in this case a linear function of w but falls off, relatively to kw , at a diminishing rate. This seems to indicate that not all the water (above 7 %) is associated with colloid; some of it exists as water wedges in the interstices between the soil particles and some of it is probably associated in a different manner with the true clay and the colloidal coating of the soil grains and it is this latter water only that is responsible for shrinkage as indicated by the fact that in silt there is no shrinkage. There is some reason for thinking (from work now in progress on the evaporation of water from gelatin) that the latter water evaporates relatively more rapidly than the former, so that for each percent. of water lost between 35 and 7 % water content a progressively larger proportion of it is "colloid" water and responsible for shrinkage while a progressively smaller proportion of it would be "non-colloid" interstitial water. Below 8 % all the "colloid" water has evaporated, only interstitial water being left and the rate curve becomes straight as in the other cases cited. Below 8 % the observed and calculated times become more and more divergent a distinct break in the curve being indicated at 7.5 % water. Between 7.5 % and 2 % the curve appears to be straight as was the case with wool and can be expressed satisfactorily by the equation $-\frac{dw}{dt} = k_2(w - c)$ in which $k_2 = 2.161$ and $c = 1$ (cf. Table I, columns 2 and 3). Below 2 % water the rate curve becomes convex to the axis of abscissae and bends round to meet the origin. It is desired to emphasise the rigidity of the test supplied by integration of the equation of rate and calculating the times and the excellent agreement between the observed and calculated times on one portion of the curve and their divergence on the other, as there is some resemblance between the writer's rate curve for Rothamsted subsoil and Keen's curve for Hoos field soil; the apparent difference in type between them might possibly be attributed merely to inaccuracy in measuring tangents graphically were it not for the strictness of the test applied and for other considerations that will be dealt with later¹. Moreover the portion near the origin is always present in all rate curves so far obtained (except with sand and silt) and since the portion xy on extrapolation would pass through the origin there must obviously be a break somewhere in the curve.

The next type of soil examined was a typically silty soil obtained

¹ See experimental part.

from Field 36 (Lower Portion) of Leeds University Farm at Garforth¹. The mechanical analysis was as follows:

	%
Loss on ignition (less moisture)	7.1
Moisture	7.5
Fine Gravel	1.3
Coarse Sand	11.1
Fine Sand	29.1
Coarse Silt	14.9
Fine Silt	17.7
Clay	11.5
	32.6

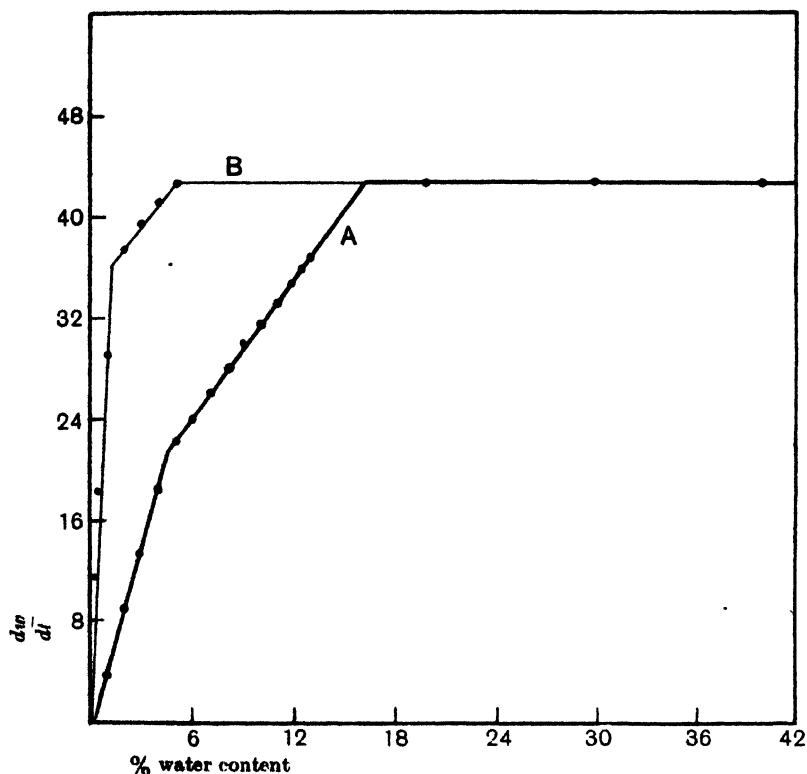


Fig. 6.

The rate curve for the soil is given on Fig. 6 (Curve A). It is essentially similar in type to the one obtained by Keen for ignited garden soil. The rate is constant, i.e. $-\frac{dw}{dt} = k_1$, down to a water content of 14.8 %. Between 14.8 % and 5.5 % the curve is straight (as was the case with

¹ The writer is indebted to Mr N. M. Comber for this sample and for details of its mechanical analysis.

wool) but does not point to the origin but to some point above it. Over this portion of the curve the equation suggested by Keen¹ for ignited garden soil obviously holds:

$$-\frac{dw}{dt} - A = k_2 w,$$

i.e. the curve on extrapolation would cut the vertical axis at a point a distance A above the origin. The integral of this,

$$\log(k_2 w + A) = -k_2 t + c,$$

is the equation of that portion of the experimental time curve between the same limits of water content. Again we have

$$2.303 \log_{10} \frac{k_2 w_1 + A}{k_2 w_2 + A} = k_2 t,$$

by means of which we can calculate times and so check the straightness of the rate curve over this range (Table II, column 5). Below 5.5 % water the curve is still straight with no indication of curvature near the origin. In this region we get again $-\frac{dw}{dt} = k_3(w - c)$ in which c is equal

to 0 and the equation reduces to $-\frac{dw}{dt} = k_3 w$.

The curve for the sample of quartz sand (Fig. 6, Curve *B*) that passed through a sieve of 100 meshes per linear inch appears to be similar to that for silt, the sharp changes of direction occurring at about 4.6 % and 1.3 % water content respectively, and c being equal to zero. The most striking thing about these two cases is the essential similarity of type of the rate curves for wool (wholly colloidal throughout with a cellular structure), quartz sand (wholly non-colloidal with a granular structure) and typically silty soil (which is notoriously feeble in colloid properties). For it is obvious that the equation expressing the rate of evaporation of water from wool between 31 and 11 % water is simply a special case of the more general equation that is applicable to the silty soil between 14.8 and 5.5 % water and to quartz sand between 4.6 and 1.3 % water; that is, a special case in which the constant A is equal to zero. The significance of this will be discussed later.

A third type of soil examined was a sample of garden soil. A mechanical analysis of this has not been carried out but it appeared to consist of a very light coarse sand with a large amount of organic matter in it. The rate curves for this sample (Curve *A*) and for the same soil ignited (Curve *B*) are given in Fig. 7. The curve is of a different type from those

¹ *Loc. cit.*

described above; it approximates roughly to a slightly unsymmetrical rectangular hyperbola. The curve for ignited soil is similar to the silt and sand type. Assuming that there was a negligible amount of clay in this sample and that the difference between the two curves is due entirely to the organic matter, the relatively small effect of organic matter on the rate of evaporation is noticeable and supports the results

Table II.

Comparison of observed and calculated results for evaporation of water from quartz sand and silty soil.

w	Silty soil (Garforth)				Quartz sand	
	$-\frac{dw}{dt}$ (obs.)	$-\frac{dw}{dt}$ (calc.)*	t (obs.)	t (calc.)†	$-\frac{dw}{dt}$ (obs.)	$-\frac{dw}{dt}$ (calc.)‡
30	42.7	—	—	—	42.70	—
20	42.7	—	—	—	42.70	—
13	36.61	37.43	2.140	2.140	42.70	—
12.5	35.38	36.41	—	—	—	—
12	34.58	35.39	—	—	—	—
11	33.00	33.35	2.290	2.293	—	—
10	31.50	31.31	—	—	42.70	—
9	29.87	29.27	2.450	2.452	—	—
8	28.01	27.23	—	—	—	—
7	26.06	26.19	2.625	2.627	—	—
6	23.93	23.14	2.720	2.720	42.70	—
5	22.175	—	2.835	2.823 [2.835]§	42.70	—
4	18.54	—	2.960	2.920 [2.956]§	40.93	41.28
3	13.40	—	3.117	3.028 [3.112]§	39.48	39.24
2	9.02	—	3.332	[3.332]§	37.32	37.20
1	3.76	—	—	—	29.03	—
0.5	—	—	—	—	18.41	—
0.25	—	—	—	—	11.49	—

* Calculated from $-\frac{dw}{dt} - A = k_1 w$, in which $k_1 = 2.041$ and $A = 10.90$.

† Calculated from $2.303 \log \frac{k_2 w_1 + A}{k_2 w_2 + A} = k_2 t$, in which $k_2 = 0.470$ and $A = 7.67$.

‡ Calculated from $-\frac{dw}{dt} - A = k_2 w$, in which $k_2 = 2.041$ and $A = 33.12$.

§ Calculated from $\log \frac{w_1}{w_2} = k_2' t$, in which $k_2' = 0.800$.

of Keen in this connection. The effect however though small, appears to be characteristic and sufficient to mask the otherwise linear character of the rate curves and organic matter when present in sufficient amount to impress its own characteristic properties on the soil mass, as in peat and humus soils, may result in a characteristic rate of evaporation curve. This is indicated also by the difference in type of the vapour pressure curves for clay loam (Fig. 2, Curve A) and for humus (Fig. 2,

Curve B), and a rate curve for peat would be interesting in this connection. At the same time it is not unlikely that the effect of organic matter on the evaporation is similar in character, although less in degree, to that of clay. Thus in the equation of rate for the Rothamsted subsoil the constant A is equal to zero. For any other clay soil it does not follow that A will be zero. A is connected in some way with average size of

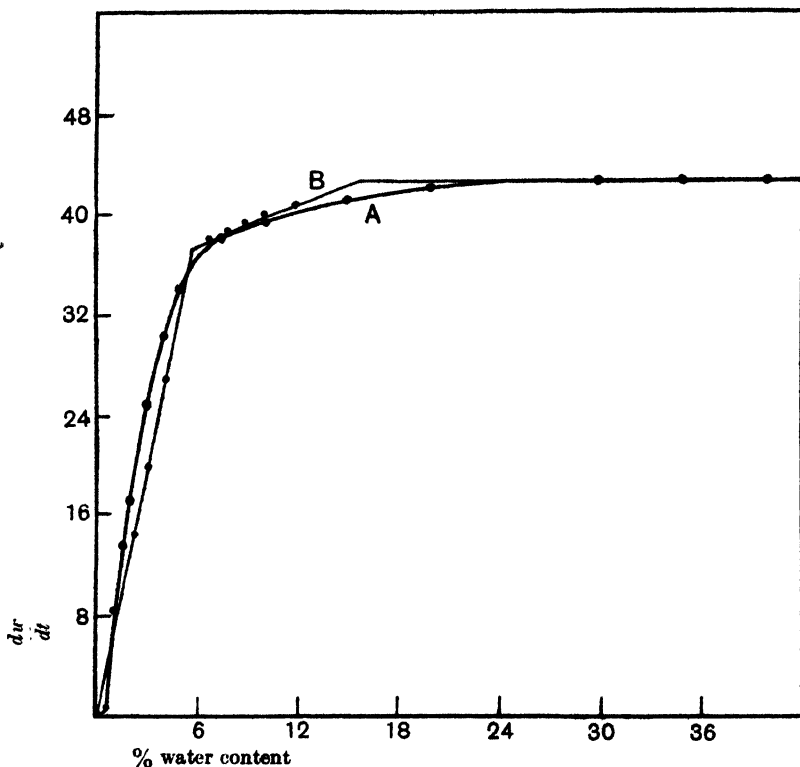


Fig. 7.

grain and with smaller clay contents A will probably have some positive value. The equation of rate would then become

$$-\frac{dw}{dt} - A - a(w - n)\frac{dw}{dt} = k_2v,$$

and the curve obtained would be similar to that for the garden soil between 24 % and 7.5 % water content. On integration this becomes

$$2.303(1 - na) \log_{10} \frac{k_2w_1 + A}{k_2w_2 + A} + a(w_1 - w_2) = k_2t.$$

Finding values for A , a and k_2 that will satisfy this equation for all values of w (w and t being obtained from the experimental time curves) is a tedious operation and satisfactory values have not so far been obtained. This point is being investigated further.

It will be observed (Fig. 6) that the first sloping portions of the rate curves for silt and for quartz sand are parallel; the corresponding portion of the clay curve (Fig. 5) would also be parallel to these if there were no shrinkage factor. In other words the constant k_2 has the same value (viz. 2.041) in all three cases. The wool curve does not fall into line with the soil curves in this respect, k_2 for the woollen fabric dealt with above being equal to 1.43. This constancy in the value of k_2 appears to be accidental in the case of the two soils dealt with; later work has shown that the value of k_2 is different with different soils. With the relatively very coarse sand the short range of water content (4.6 % to 1.3 %) combined with slight curvature of the experimental time curve makes it difficult to determine the exact value of k_2 and the identity in value of $k_{2(\text{sand})}$ and $k_{2(\text{soil})}$ is probably only apparent.

The moisture contents at which the rates of evaporation begin to fall off, i.e. at which the vapour pressure of the retained moisture begins to diminish, are characteristic for each soil. They are some function of the total surface of the soil grains which in turn is dependent on the average size of the grains. This water content may therefore be used as a means of characterising a soil.

In the case of a clay soil the shrinkage due to the content of real clay should be allowed for before making use of the critical moisture content as a means of designating a soil; such a correction however does not affect the value of A . On the other hand the degree of shrinkage in such a soil, being a function of the water content, is related to the value of a and may also be some simple function of the real clay content, that is to say, not of the magnitude of the clay fraction as determined by ordinary mechanical analysis (since this, as is apparently the case with silty soils, may contain very little actual clay) but of that portion that is responsible for the shrinkage and which is presumably real clay. It is possible that a may prove of value in characterising a soil as regards its clay or colloid content. Much more work will be necessary along these lines before rate curves can be used as a basis for classifying soils especially in view of the possibly disturbing effect of the presence of organic matter on the rate curve as discussed above, but it is not unlikely that if such a basis were found to be practicable it would present some advantages over the present tedious method of mechanical analysis.

An interesting aspect of the results so far dealt with is their bearing on the physical nature of the soil complex. The earlier work on evaporation seemed to indicate that the relation between the moisture content of a soil and the vapour pressure was more complex than is the case with sand or silt since the rate curve in the former case was nowhere linear. The rate curve appeared to be roughly exponential throughout its entire course and Keen showed that his curve was fitted by an exponential type of equation if this is modified by the introduction of a shrinkage factor as already described. The agreement found was good except at very low water contents and Keen inferred from this that his second equation gave an empirical measure of the influence of vapour pressure on the rate of evaporation in the case of clay soils, the relationship being much simpler with silt and sand and ignited soil. This difference in relationship was held to be associated with the colloid properties of clay and this early work has been widely quoted as direct evidence in favour of the modern theory of the colloid constitution of the soil, viz. that the colloidal matter present forms a gelatinous coating over the surface of the soil grains. The direct measurements of Thomas¹ and of Sven Oden² showed however that there is no difference in type between the vapour pressure curves of sand, silt or clay, all of them approximating to rectangular hyperbolae, while the work described above shows clearly that the whole of the curvature in the case of a clay soil is due to shrinkage and that where this effect is absent the rate curve is linear (except possibly when large quantities of organic matter are present). On the other hand one cannot infer from a linear rate curve that no colloid is present in the soil nor even that no clay is present but only that no appreciable shrinkage occurs on drying out, for linear curves are obtained with such essentially colloidal material as wool when this possesses a (cellular) structure of sufficient rigidity to overcome the tendency to shrink on drying. It is only when clay is present in sufficient amount to impress its own particular properties on the whole soil mass that a typically "curved" rate curve is obtained. Thus the silt soil dealt with above contained 11.5 % of clay, but it is probable that most of this was real clay only in name and size of particle, for no appreciable shrinkage or cracking or caking occurred during the drying in striking contrast to the behaviour of the Rothamsted subsoil. In general the similarity in the wool, sand and silt curves indicates clearly that a colloid merely as such has no characteristic rate of evaporation curve; it is only when other

¹ *Loc. cit.*

² *Trans. Far. Soc.* 17 (1922), 244-8, 288-94.

factors come into play, such as shrinkage in the case of clay, or when the chemical or physico-chemical properties of the material exert their effect, as with gelatin and certain terrestrial algae, etc., that certain peculiarities are impressed on the rate curves—peculiarities that have hitherto been almost universally ascribed to some peculiar property of the colloid state. It is evident that the forces binding the water to the material are not dissimilar in wool, sand, silt and clay, except possibly at very low water contents. Consideration of the effects of osmotic and other physico-chemical factors on the rate of evaporation from colloid materials is reserved for later communications. In passing it may be pointed out that the apparent absence of peculiarities in the moisture relationships of colloids as reflected in the evaporation curves falls into line with the recent brilliant work of Loeb¹, who has shown with a logic almost beyond controversy that the laws of classical chemistry are adequate to explain the so-called colloid behaviour of proteins.

Experimental. As stated above the experimental method and apparatus devised by Keen has been used throughout this investigation with only minor modifications. The work was carried out at 25° C. in the case of wool and at 28° C. with soil. The preliminary treatment and in particular the method of wetting the material was different and accounts to some extent for some of the differences between the writer's results for soil and the earlier ones. Apart from the apparatus used the method of wetting the material in order to establish uniform distribution of moisture throughout the mass is undoubtedly the most important experimental consideration and unless such uniform distribution is ensured quite different types of rate curves may be obtained. Mere reproducibility of experimental time curves and excellent agreement between duplicate series are no criterion and in fact an accumulation of perfectly consistent and concordant results collected over a period of two months was rendered useless by making use of such a criterion in the case of wool. A woollen fabric was used (which had been previously extracted in a Soxhlet apparatus with petroleum ether and absolute alcohol successively to remove oil and soap) and this was cut into pieces 3½ inches long by 2½ inches wide. During the drying each piece was suspended on four pins at the corners of a small aluminium frame. The first method of wetting adopted was to thoroughly spray each piece on both sides with water from an atomiser; the water was carefully smeared over the surface with a clean glass rod, the spraying and smearing were repeated two or three times and the fabric was then suspended on its frame and

¹ *Proteins and the Theory of Colloidal Behaviour*, J. Loeb (McGraw-Hill Pub. Co.), 1922.

exposed to a saturated atmosphere over water for about 20 hours. With a number of different fabrics perfectly consistent, concordant and reproducible curves resulted, but the rate curves were very different from those finally obtained and described above; they were perfectly smooth and continuous, with no sharp changes of direction and were very pronouncedly sigmoid. They resembled the vapour pressure curves and were below them throughout their entire length except at the origin and the extreme "wet" end where they coincided. It was the difficulty experienced in getting concordant duplicates in the case of particularly thick and coarse milled fabric that threw doubt on the efficacy of this method of wetting. In the method finally adopted the fabric was placed in water in a filter flask and the pressure reduced to 2-3 cm. of mercury until no more air bubbles were disengaged from the fabric. The normal atmospheric pressure was resumed and the material was allowed to soak for an hour after which it was removed, lightly centrifuged for half a minute at 500-700 R.P.M. to remove loosely adhering water and was then placed as before in a saturated atmosphere for 20-24 hours. In this way good results were obtained in all cases even with the thickest and coarsest of fabrics. It was found afterwards that soaking in water without reducing the pressure was equally effective and this method was adopted with soil although the vacuum treatment was adhered to in the case of wool.

The soil samples after passing the 1 mm. sieve were stirred up with a slight excess of water and sufficient ammonia added to make the mixture faintly alkaline—just sufficiently so to maintain the soil in the deflocculated condition. In this way both deflocculation and uniform distribution of moisture are ensured. The mixture was then made approximately neutral with HCl. The condition of the sample is obviously in no way comparable to its condition in the field but in an investigation of this nature no particular merit can be attributed to "field conditions" as the most important consideration is the attainment of a condition of equilibrium in a soil-water system that can be reproduced at will. The wet soil sample was placed in a circular aluminium tray $2\frac{3}{4}$ in. in diameter and about $\frac{3}{8}$ in. deep and was kept in a saturated atmosphere overnight. Any excess water may be removed with blotting paper or in the case of the heavier soils by a preliminary exposure over sulphuric acid. The important thing is that a steady state of evaporation be reached and the weighings commenced while the system is still in the condition represented by the first horizontal portion of the rate curve, i.e. when the evaporation is taking place from a free water surface. It

is obvious that when the water content corresponds to a point on the sloping portions of the rate curve the vapour pressure must be less than that of a saturated atmosphere and exposure over water in a closed vessel overnight will merely result in the establishment of what may be termed a concentration gradient inwards, equilibrium being attained only after a very long time—possibly months. If the system is in such a condition at the beginning of a series quite a different rate curve may result and this point has apparently been overlooked in earlier work on this subject. The point is of such importance that its effect on the rate of evaporation may be illustrated by reference to a preliminary drying of a sample of alga (*Pleurococcus*). This was dried each day for seven days being removed from the apparatus each night. For the first four days evaporation was proceeding from a free water surface and all the points obtained fell on the same straight line. During the sixth and seventh days the rate was falling off progressively. During the sixth night the tray was removed from the bath, covered with tinfoil, and left on the laboratory bench. During the night moisture was absorbed from the atmosphere and a concentration gradient established inwards. The drying curve obtained on the seventh day consequently overlapped the curve obtained on the sixth day but the overlapping portions were not identical although in each case the first half-hour's drying was not taken into account so that sufficient time might be allowed for a steady state to be reached.

In conclusion it is a pleasant duty to record my indebtedness to Dr B. A. Keen, not merely for the inspiration of his early work in this field but for much helpful criticism and advice resulting from fruitful discussions on many occasions. Thanks are also due to Mr G. C. Steward, Fellow of Gonville and Caius College, Cambridge, for help in clarifying my ideas on some of the more mathematical points involved.

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COD LIVER OIL IN THE WINTER FEEDING OF MILCH COWS.

BY

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McCOLLUM, SIMMONDS and PITZ (1916) (1) were the first investigators to show that the milk secreted by a lactating female will be deficient in the vitamins A and B unless her diet contains adequate amounts of these substances, and a considerable amount of confirmation of this observation has since been brought forward from other sources. The variations in the vitamin A-content of the butter yielded by cows were studied by Drummond, Coward and Watson (1921) (2), who demonstrated that the chief cause of such variations lies in the diet of the animal. Hopkins (1920) (3), however, was unable to trace any marked difference between the vitamin concentration of goat's milk yielded on a ration of mixed cereals, hay and mangolds and that given when the diet was supplemented with green food. The yield of milk was greater in the latter case but the proportions of total solids and fat were the same in both cases.

Hughes, Fitch and Cave (1921) (4) stated that both vitamins A and B are found in higher concentration in milk derived from cows on a diet rich in those substances than in milk from animals fed on a deficient ration. More recently Kennedy and Dutcher (1922) (5) have reported a full series of experiments on this question, and have arrived at the conclusion that the presence of both vitamin A and B in the milk is dependent on their occurrence in the ration. They point out, however, that a milk rich in vitamins is not necessarily correlated with access to pasturage, but

that such milk can be obtained from stall-fed cows provided that their ration is compounded from a proper combination of grains and leafy foods; an observation which is of considerable practical importance. When their paper appeared we were in the middle of a series of experiments planned to test whether it is possible and practicable to maintain the vitamin A-content of cow's milk by administering small supplements of a very rich source of that factor, such as cod liver oil, during the period when the animals are usually receiving an indoor ration tending to be deficient.

The general plan of the experiment was to study a group of cows late in the year, and, having determined the vitamin A value of their butter fat at the close of the grass-feeding season, to place them indoors on a typical winter ration deficient in that vitamin until an examination of the fat showed that the concentration of the accessory factor had dropped considerably. The group was then to be sub-divided into two lots, one of which was to receive a daily dosage of a highly potent cod liver oil whilst the other would receive an equivalent dosage of an inactive oil to serve as a control.

Actually two additional groups were introduced in order to study the influence of more or less restricted grass feeding during winter months, such as is usually practised in the south of England.

The groups were as follows:

Group I. (Winter Feeding in Stall.)

Name of cow	Breed	Age	Date of last calf	Remarks
"Fillpail II"	Shorthorn	7 years	6th calf 28. xi. 21	
"Crocus"	"	3 "	1st " 16. xi. 21	
"Cowslip"	"	3 "	1st " 11. xi. 21	
"Ruby"	"	8 "	6th " 27. i. 22	Not introduced to group until 5. ii. 22

Notes on Group I. During the "dry" period preceding calving all the cows had the run of a pasture field and, with the exception of "Ruby," received nothing but grass. "Ruby," owing to the diminished amount and quality of the December and January grazing, received mangolds and hay in the field and 4 lb. of linseed cake, crushed oats and bran daily. At calving time "Crocus," "Cowslip" and "Ruby" were in good condition; "Fillpail II" was in poorer flesh than the others and not so well prepared for the strain of the lactation period. All the cows calved normally, but "Ruby" gave birth to twins and the consequent strain reduced her condition somewhat. After calving and from the commencement of the experiment on December 4th the cows "Fillpail II,"

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"Crocus" and "Cowslip" were fed on a diet of mangolds, hay and concentrated foods, the actual amounts being set out in the Table I.

Table I. *Feeding of Cows maintained entirely on Indoor Feeding.*

Cows				
"Cowslip"	1st calf born November 11th, 1921			
"Crocus"	" " " " 16th, "			
"Fillpail II"	6th " " " 28th, "			
"Ruby"	" " " January 27th, 1922			

Feeding: From December 17th, 1921, to May, 1922.

Daily basal ration throughout period: Mangolds, 50 lb.; seeds hay, 17 lb.

	Milk mixtures	"Cowslip"	"Crocus"	"Fillpail"	"Ruby"
December 17th to January 21st	{ Maize gluten feed, 4 pts Maize meal, 5 pts Dec. ground nut cake, 3 pts }	lb. 8	lb. 9	lb. 15	lb. --
January 21st to February 11th	{ Maize gluten feed, 4 pts Maize meal, 2½ pts Crushed wheat, 2½ pts Dec. ground nut cake, 3 pts }	8	8	15	--
February 11th to April 1st	{ Maize gluten feed, 4 pts Maize germ meal, 2½ pts Crushed wheat, 2½ pts Dec. ground nut cake, 3 pts }	7	7	15	15
April 1st to May	{ Dec. cotton cake, 2 pts Crushed wheat, 2 pts Maize germ meal, 1 pt Maize gluten feed, 1 pt Dec. cotton cake alone }	4	4-3	15-12	15

The mangolds given were whole, whilst the slight changes in the cake and meals caused by changes in supply were only such as commonly take place in the course of the winter season. The hay was made from clover and legumes with some cocksfoot, and was of excellent quality. The cows were housed at night and during the greater part of the day but were turned out for a short time each morning in a bare yard for water and exercise. From December 4th, 1921, until the end of the third week in May they received no supply of grass or other green food.

Group II. (Very limited pasture in winter.)

The cows in this group were selected from a small herd belonging to the National Institute for Research in Dairying. All were of the Dairy Shorthorn type. The feeding from December to April was on the same lines as that of Group I, with the exception that from February onwards the cows were turned out for a short time each day in a small paddock where only a very small amount of grass was available.

Group III. (Maximum winter pasturage.)

The cows in this group were selected from a small herd owned by University College, Reading, and were of the Dairy Shorthorn type. The feeding of this group consisted of mangolds, hay, straw, chaff and concentrated foods as in the case of the other two groups, but throughout the winter whenever the weather permitted they were turned out into a field where as spring advanced they were able to obtain an appreciable amount of fresh grass. As the winter was on the whole a mild one, especially latterly, they were out rather more than is usually possible.

Records of milk-yield at each milking were made in the case of each individual cow, and in the case of the most important group (I) the milk was tested twice daily for fat-content and specific gravity. In order to test the changes in vitamin A-content of the milk fat samples of butter were made at certain periods from the mixed milk of each group and these were tested in the usual manner on rats. In addition, the samples of butter were subjected to a complete chemical analysis, in order to ascertain whether the changes in nutritive value were associated with changes in any of the usual analytical data.

Results on Group I. Effect of the winter ration deficient in Vitamin A.

This group were maintained on the ration deficient in vitamin A and consisting of mangolds, hay and concentrates from December 3rd, 1921, until March 5th, 1922. During this time the yield of milk from each cow and the percentage of fat did not show any variations outside the normal range.* There was, however, a very marked and surprisingly rapid decrease in the amount of natural pigment in the milk fat which was associated with a somewhat parallel fall in the vitamin A-value. These decreases may be judged from the following relative values:

Date of sample of butter	Period on indoor diet	Units of pigment	Approximate growth dosage *
December 3rd, 1921	Commencement	1.4	0.1 gm.
January 31st, 1922	59 days	0.5	1.0 "

* The dosage is inversely proportional to the vitamin-concentration and roughly represents the weight of daily supplement which just gives definite growth in a 100 gm. rat.

About the middle of February the growth dosage of the butter showed a definite improvement to a value of 0.4 gm.

For some time we were unable to account for this sharp rise, but we are now inclined to attribute it to the inclusion of "Ruby" which had

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calved on January 27th, and which was introduced into the group on February 5th, this being necessary in order to make an even number in the group for subdivision later. Although "Ruby" had been indoors for some time before calving we unfortunately ignored the fact that she would have had storage of vitamin A in her tissues preparatory to lactation. Whatever was the cause of this rise it was not observed in time to allow of a modification of the experiment. Even with this disturbance the vitamin A value of the milk on February 28th, 1922, was less than a quarter of that when the cows were brought in from grass on December 3rd, 1921. It was therefore decided to carry out the tests with cod liver oil. Accordingly the group was subdivided into two groups of two cows:

<i>Group 1 a.</i>		<i>Group 1 b.</i>	
"Fillpail II"	} Cod liver oil	"Crocus"	} Inactivated olive oil
"Cowslip"		"Ruby"	

The oils were given in the raw state to the cows directly each day and in gradually increasing amounts as follows:

	gm. per day
March 4th–March 23rd	15
March 23rd–April 27th	30
April 27th–May 16th	60
May 16th–May 20th	90
May 20th–May 31st	120

} "Crocus" and "Cowslip"

For the cows "Fillpail II," and "Ruby" the experiment ended on May 17th, 1922, when they were turned out to grass. "Cowslip" was given increasing supplements of cod liver oil to see whether large doses of that product would eventually cause taint in her milk or butter. "Crocus" was given equal weights of olive oil as a control.

The sample of cod liver oil used was one of good quality and possessing a clear golden yellow colour. It had been previously tested on rats and found to be highly potent as a source of vitamin A. The control cows received an equal daily dose of olive oil which had been heated for three hours at 120°C., with a current of air bubbling through it in order to oxidise and destroy any traces of the vitamin which might have been present.

Influence of Cod Liver Oil Feeding on Milk Yield and Fat.

Examination of the milk records for the "oil" periods, fails to show any marked variation from the normal figures. It is possible that the number of animals under investigation is too small to enable conclusions to be drawn from the available data, but there was no obvious difference between the curves of milk yield from the cows on cod liver oil and those on olive oil. The routine estimations of fat by the Gerber method

also failed to show any striking change which could be attributed to the administration of one or other oil. When, however, the cows were turned out to grass at the end of the experiment the usual rise in the milk yield was seen.

Influence of Cod Liver Oil on Vitamin Value of Milk Fat.

During the period of administration of cod liver oil there was a steady and very marked rise in the vitamin value of the butter fat yielded by the two cows "Fillpail II" and "Cowslip." This rise was accompanied by a very slight fall in the amount of pigment.

Date of sample	Period on cod liver oil days	Dose during preceding period gm.	Pigment value	Approximate growth dosage gm.
February 28th	0	0	0.6	0.4
March 23rd	23	15	0.5	0.4
April 26th	34	30	0.45	0.2
May 24th ("Cowslip" only)	28	60-120	0.35	0.1

The two control cows receiving the inactivated olive oil showed a definite improvement in the vitamin content of their butters as the experiment progressed, although at the end of the experimental period the butter value was still considerably below that of the cod liver oil group. We have as yet been unable to account for this rise, which is contrary to the idea of a gradual exhaustion of the reserves of the body during prolonged feeding on a deficient winter ration. We hope to obtain more light on this question in a series of experiments which are now being undertaken and in which larger groups of animals and more rigorous control of the basal diet will be ensured.

Influence of Cod Liver Oil Feeding on Taste and Flavour of the Milk and Butter.

Throughout the experiment there was no fishy taint in the samples of milk or butter yielded by the group to which the cod liver oil was administered, even when the dose was as high as 120 gm. (4 oz.) daily. This should help to remove the long-standing prejudice against the use of such oils on the grounds that by their use flavour and taste may be impaired. It is necessary, however, only to employ oils of high grade. This subject is treated in more detail in the next paper.

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Influence of Restricted Grass Feeding during Winter.

As described above Groups 2 and 3 received a certain amount of grazing during the winter when weather permitted, and an examination of the butters yielded during this period shows very clearly the gradual rise in vitamin A concentration, associated with a rise in lipochrome pigments, which occurs as the pasture freshens in the early part of the year.

Group 2. (Grass for short time on fine days after January 30th.)

Date of sample	Pigment value	Approximate growth dosage gm.
January 31st, 1922	1.20	0.8
February 28th, 1922	1.00	0.8
March 29th, 1922	1.30	0.6
April 26th, 1922	2.20	0.2

Group 3. (Grazing from 9 a.m. to 2 p.m. on fine days.)

Date of sample	Pigment value	Approximate growth dosage gm.
January 31st, 1922	1.20	0.8
February 28th, 1922	2.05	0.8
March 29th, 1922	1.70	0.2
April 26th, 1922	2.35	0.2

It is interesting to observe that in spite of grass feeding, which in the case of Group 3 was fairly liberal towards the end of the experimental period, the vitamin value did not appear to rise quite as high as that of the butter yielded by the cows receiving 60 gm. of cod liver oil daily.

It is possible that other factors showing a seasonal variation, such as the amount of direct sunlight, may have to be considered in the set of experiments which are now being carried out, but at present we do not lean to the belief that solar radiation has directly been the cause of any of the variations which we have encountered in this work. This view is to some extent confirmed by the results of some tests on butter which we were enabled to examine from another experiment made at Wye Agricultural College, Kent. For opportunity to examine these butters, for details of that experiment and permission to incorporate the results in this paper we are indebted to the Director and Mr V. C. Fishwick. The object of the experiment at Wye was to ascertain the relative value of ensilage and mangolds in the winter feeding of cows. Two groups of four cows were fed on the following rations (1200 lb. cow).

Ensilage group	Mangold group
Ensilage, 45 lb.	Mangolds, 56 lb.
Hay, 6 lb.	Hay, 8 lb.
Oat straw, 6 lb. (about).	Oat straw, 8-10 lb.
Concentrates, 4 lb. per gallon of milk yielded after the first.	Concentrates, 1½ lb. (maintenance) 4 lb. per gallon of milk yielded.

The ensilage used was a spring-sown crop of oats and tares, whilst the composition of the concentrated mixture was:

Oats	50 %
Uncorticated Cotton Cake	25 „
Linseed Cake	25 „

It will be seen that any difference in the vitamin value of the butter yielded by the two groups would probably be attributable to the influence of the ensilage and mangolds.

After a period of about a month the groups were changed over on to the other diet and again after a further period were again brought back to their original rations.

It was found by our feeding tests that butters from both groups possessed a very low vitamin value. There was just an indication that the sample yielded by the cows on the ensilage group had a slightly higher nutritive value than those from the mangold group, but it is questionable whether the difference was outside the range of experimental error.

In conclusion we would wish to express our thanks to Mr Alec Todd, of the British Dairy Institute, for making the butters, to Mr G. Napier and Mr W. S. Ferguson for the routine analyses of the butter samples, and to Mr A. Wagstaff for the daily analyses of the milk. We are also indebted to the Medical Research Council for a grant from which the expenses of this work were defrayed.

SUMMARY.

1. Further confirmation is presented in support of the relationship between the presence of vitamin A in the milk and its supply in the food.
2. The influence of the supply of the vitamin A in the food on the quantity or fat content of the milk is uncertain, in any case it appears to be much less than that produced by turning the cows out to grass.
3. The increase of the vitamin A-content of the milk produced by feeding cod liver oil is not accompanied by a rise in the lipochrome pigments as is the case when the cows are turned out to grass.

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4. Up to 4 ounces per day of a good quality cod liver oil produced no fishy flavour in the milk or butter of one cow, but further experiments appear desirable.

5. Stall feeding even when ensilage was used causes the winter-milk to be lower in vitamin-content than summer milk; this is mitigated by such restricted grass feeding as is possible in the south of England.

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THE USE OF COD LIVER OIL IN THE FEEDING OF FARM ANIMALS.

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IN an empirical manner cod liver oil has been used for many years as an occasional food for farm animals. Generally speaking, its use has been chiefly confined to the rearing of calves and to improving the condition of horses. It is difficult to glean from the literature of animal husbandry information about the use of this oil, but it would appear that whilst the majority of authorities favour its employment in small amounts in special cases others are inclined to regard the oil with suspicion. Thus, Campbell (1900) (1) recommends cod liver oil as an efficient substitute for cream in the rearing of calves; a conclusion that was confirmed in a later publication from the Leeds Station (Seton, 1901) (2). These reports warn users against the inferior grades of oil and show that if good preparations are used there is no detrimental effect on the flesh when animals are afterwards slaughtered as bullocks.

Pott (1909) (3) is distinctly in favour of the oil and quotes numerous examples of its beneficial action in the rearing of calves and the cure of rickets in pigs. In particular he quotes an English farmer, a Mr Harris of Essex, who regularly fed his cows morning and evening with a supplement of cod liver oil and who was convinced that this addition was responsible for a great improvement in the general condition of the animals. That this addition had no deleterious effect on the taste of milk and butter is indicated by the remark:

“er nie eine so wohlschmackende und nie so viel Milch und eine so feine Butter als nach der Lebertransverfütterung erhalten habe.”

Hendrick (1913) (4) remarks: “It has become an almost established canon during the past ten years that it (cod liver oil) is the one oil which is eminently suitable for this purpose (i.e. replacing the fat in milk for calf feeding).” A favourable opinion was also held by Voelcker (1914 (5) and 1917 (6)), but more guarded statements are made by Lindsey

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(1893-4) (7) and by Tod (1915) (8), both of whom sound a warning that it may sometimes cause digestive disturbances in animals.

It is not claimed that the above extracts are a summary of the opinions on the employment of cod liver oil in agriculture, but they show that there is a definite majority in its favour, and from enquiries which we have been making recently it is apparent that this majority is steadily increasing. We have for some years past been making an extensive study of cod liver oil from many aspects and from our accumulated results we believe that the extracts which make up the present communication will be of interest and practical importance to agriculturalists.

THE NUTRITIVE VALUE OF COD LIVER OIL.

In all the extracts quoted above cod liver oil was regarded as a nutrient, supplying as it does an ingredient of high calorific value and tending to balance a ration rich in nitrogenous constituents and low in oil.

From this point of view cod liver oil compares favourably with other possible substances such as linseed oil, which are often added to separated milk to restore the balance of nutrients found in the natural diet of calves.

The beneficial influence of cod liver oil cannot, however, be explained on the basis of its value as an oil *per se*.

In the past there have been numerous theories to explain the undoubtedly high nutritive value of cod liver oil and its exceptional value in the treatment of wasting diseases and poor condition. It will be sufficient for the purposes of this paper to take the three main theories which have held ground for many years. These have been, first, the theory which held that the minute traces of iodine present in some samples of cod liver oil are responsible for the specific therapeutic action; secondly, a similar theory which attributed the action to the presence of minute traces of obscure nitrogen bases in the oils; and, lastly, the theory that the peculiar nature of the unsaturated fatty acids of cod liver oil rendered it particularly readily absorbed and utilised by the poorly-nourished organism.

Osborne and Mendel, in America (1914) (9), have shown that cod liver oil also contains a substance which McCollum and Davies (1913) (10) had found in butter and which plays an important part in the regulation of the growth of the animal body. More recently Zilva and Miura (1921) (11) have demonstrated the important fact that cod liver oil contains this principle in very great abundance, namely several hundred times as

much as butter. The fact that the whole of the specific action of cod liver oil on growth can be concentrated into the unsaponifiable fraction of the oil has rendered the third theory quoted above untenable (McCollum and Davis (1914) (12), Steenbock and Boutwell (1920) (13), Coward and Drummond (1921) (14)), whilst the other two are also dismissed by the fact that this fraction may be obtained in a highly active form free from any trace of iodine or nitrogen. The physiologically active substance is by general consent named Vitamin A. For a complete review of this substance readers are referred to the excellent monograph, *The Vitamins*, by Sherman and Smith, and published by the American Chemical Society, or to the *Report* published by the Vitamin Sub-Committee of the Medical Research Council, Special Report No. 38 (revised edition now in preparation).

MARKET QUALITIES OF COD LIVER OIL.

In a recent paper Drummond and Zilva (1922) (15) have given an account of their close study of the Norwegian cod liver oil industry made during a visit to Norway last year. The information they obtained then has since been supplemented by that yielded by a similar study of the industry in Great Britain and in Newfoundland.

The best quality of cod liver oil is prepared with great care by steaming the absolutely fresh livers in vats for about half an hour. The oil rises to the top and is skimmed off as a clear white or very pale yellow product. It is later refined for medicinal use by freezing at low temperature and filtering off the separated "stearin," the final product being a crystal clear oil which remains clear at temperatures about 0° C. Such oils are usually rather expensive for cattle feeding. Further treatment of the liver residues is often carried out whereby second and third fractions of oil are prepared. This treatment sometimes consists of a reheating of the livers, whilst in other factories a draining of the residues through canvas bags or expression in a press is employed. In most cases these latter fractions are slightly more coloured than the first fraction and although they are sometimes mixed with the latter and sold as medicinal oil they are perhaps more frequently kept apart and sold as cattle oils.

Particularly in Norway it is customary to allow the liver pulp after preparation of the first, or perhaps the first and second fractions, to rot in open vats exposed to the air for several months. By this treatment a considerable further amount of oil is liberated from the rotting mass and rises to the top. Such oils are usually dark in colour and vary from

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a golden-yellow to a deep golden-brown colour. Our information leads us to believe that the majority of such products are originally sold for industrial use, but there is evidence that some of it is eventually retailed for cattle feeding.

In addition to oils which have been prepared from fresh livers or from their residues there is a fair bulk of oil prepared, especially in this country, from livers which are far from fresh when steamed. The reason for this is that in Norway and Newfoundland the boats return to port within a few hours of hauling in the catch, whereas the fishing fleets from Grimsby, Hull, Aberdeen and other British ports are often away for several weeks at a time fishing the far northern waters. In such cases the fish are gutted on board and packed in ice whilst the livers are thrown into barrels on deck and are regarded as perquisites of the fishermen. The time elapsing before the livers are landed is variable but it is seldom short enough to ensure the absence of putrefactive change, and sometimes the contents of the barrels are a foul-smelling, greyish-green slime when they are sold by the fishermen to agents of the oil manufacturer at the quayside. This material is steamed in vats in the usual manner and yields a considerable amount of oil possessing a colour varying from golden-brown to almost a brownish black. The main bulk of such oil appears to go to the soap-boilers or the leather industry, but quite an appreciable amount is offered for cattle feeding in one form or another. There is a relatively small amount of oil prepared from fresh livers in this country and its quality is excellent, but it is doubtful, however, whether this amount is likely to increase to any great extent owing to the unlikelihood of the supply of fresh livers being increased appreciably.

Drummond and Zilva have examined by chemical analysis and by feeding experiments on small animals nearly two hundred samples of cod liver oils of all types. From this list we have selected a few typical analyses in order to show the essential differences between the main classes of oils (Table I).

It is usual to apply the name "Cod Oil" or "Coast Cod Oil" to the crude oils which are prepared from the stale livers. As a result of the decomposition changes which have gone on in the liver tissue such oils are characterised by possessing a deep golden-brown or brown colour and a most pronounced and objectionable fishy odour. They also show a high acid-value and contain appreciable amounts of substances derived from the decomposing protein of the livers, such as the putrefactive bases described by Gautier and Mourgues (1888) (16) and by Hawk (1908) (17). The latter author showed the origin of these nitrogen bases when

Table I. ANALYSES AND GROWTH VALUES OF COD LIVER OILS.

Sample number	Origin	Remarks	Colour	Acid value	Saponif.-cation value	Iodine value	Total N %	Total P %	Colour test dosage* mg.	Quality
K 1	Norway, Finnmarken	Cod and haddock	Very pale Lemon-yellow	1.71	191.8	147	nil	trace	8 12	Medicinal
K 3	"	"	"	1.73	190.7	159	nil	trace	10 12	"
K 22	"	"	Lemon-yellow	2.60	189.4	149	0.008	0.004	12 5	Medicinal or good quality cattle
K 24	"	(2nd fraction oil by draining residues)	"	2.11	190.2	152	0.007	0.004	6 25	Cattle oil or industrial
K 5	"	"	Pale golden-brown	8.76	195.2	142	0.010	trace	4 12.5	Cattle oil or industrial
H 2	"	"	Golden-brown	4.35	184.4	153.5	0.03	0.002	10 8	Cattle oil
L 3	" Lofoten	"	Golden-brown	7.44	191.5	167.7	0.015	0.005	4 50	Cattle or industrial
H 11	E. coast, England	From putrid livers	"	14.4	184.5	147.2	0.02	0.002	6 50	Industrial
H 12	"	"	Dark brown	21.4	189.5	155.3	0.03	0.003	8 25	"
H 13	"	"	Very dark brown	21.5	179.8	186.2	0.05	0.006	6 50	"
N 3	Newfoundland	"	Deep golden-brown	26.0	193.3	156.7	0.025	0.005	8 12	"
N 4	"	From liver pulp by rotting	Golden-brown	1.95	188	156	0.012	trace	8 12	Cattle or industrial
G 1	E. coast, England	From putrid livers	Deep golden-brown	23.11	184.1	175.6	0.036	0.0026	5 50	Industrial
G 2	"	"	"	25.64	178.9	179.4	0.040	0.0028	4 50	"
J 4	Newfoundland	2nd fraction from fresh livers	Golden-yellow	1.48	190.2	156.2	0.007	trace	13 8	Cattle
R 1	?	Commercial cattle oil	Deep brown	17.40	—	—	0.025	0.004	13 8	"

* (growth dosage represents the weight in milligrams of the oil which just maintains steady growth in a test rat of about 100 gm. body weight. This figure is therefore inversely proportional to the concentration of vitamin in the oil.

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he found the amount was proportional to the extent of the previous putrefaction in the liver. The following figures show the amounts he isolated:

"Light amber" oil	0.106 %
"Light brown" oil	1.117 ,,
"Dark brown" oil	1.09 ,,

A similar parallel is shown in our determinations of nitrogen recorded in Table I.

Many of the commercial cattle oils are prepared from the liver of mixed fish, but in our opinion this is no drawback to their use since we have shown (Zilva and Drummond (1921) (18)) that many species other than cod contain large amounts of the vitamin in their liver.

QUALITIES OF COD LIVER OIL FOR CATTLE USE.

There can be little doubt from our perusal of the available literature and from our own experience that the complaints of tainting of flesh or dairy products after the use of cod liver oil or the incidence of digestive disturbances in the animals so fed are due almost entirely to the employment of very low grade oils, or perhaps to too high a dosage. It is difficult to lay down a standard for oils for cattle feeding in the light of our relatively limited practical experience, but we would like to put forward the following suggestions. A sample of cod liver oil for cattle feeding should be clear and bright and preferably not be of a deeper colour than golden-yellow. It should have an acid value below F.F.A. = 10 % and should give a strong purple colouration when three drops of the oil are dissolved in three c.c. of petroleum spirit (redistilled b.p. 40-50) and one drop of concentrated sulphuric acid is added.

This old test for liver oils has recently been re-examined (Drummond and Watson (1922) (19)), who have shown that there are indications that the response to this test is roughly parallel to the vitamin value of the oil. We do not wish to emphasize this relationship, if indeed it actually exists, but we feel nevertheless that the test may be useful in detecting adulteration with fish oils other than those derived from livers, or attempts to bleach dark oils by various means. Adulteration of liver oils with such oils as whale or seal oils may occur and will tend to diminish the response to the colour test, whilst any attempt to remove the pigment of darker oils by bleaching methods involving oxidation will destroy the chromogenic substance as well as the vitamin. The probability of an increase in the demand for cattle cod liver oils makes it highly probable

that both adulteration and efforts to put inferior oils on the market, either bleached or disguised in the form of feeding mixtures, will take place to a much greater extent than now occurs.

At the present time (December, 1922) genuine cattle cod liver oils of high grade can be purchased in this country from reliable makers at the following approximate prices (containers included):

Small quantities	6s. per gall.
Larger bulk	3s. 6d.-4s. per gall.

Such oil is usually of clear golden-yellow colour and has an acidity below F.F.A. 8 %. It gives a strong colour reaction with the sulphuric acid test and has an odour rather more pronounced than a medicinal oil, but not definitely objectionable as in the case of the dark brown industrial oils or cod oils.

COD LIVER OIL IN THE FEEDING OF FARM STOCK.

Having emphasized the advisability of employing oils of high grade we would next wish to point out the surprisingly small amounts of such oils which are effective in bringing about the desired result. This has been first brought to our notice in our purely scientific experiments in which rats are used as the test animals. In such cases we find that an average daily dose of 10 milligrams of oil is usually sufficient to supply the requirements of a young rat of 100 gm. body weight. Such an amount represents only 0.07 % of the daily food intake, whilst in the case of oils of exceptionally high potency this figure may be as low as 0.013 %. Equally small supplements, proportionately, are effective in the feeding of farm stock, a fact which should impress the practical mind that these oils have a nutritive value which cannot be expressed solely in terms of "oil" or calories.

Our own experience in the use of cod liver oil in the feeding of farm stock has mainly been limited to pigs and milch cows.

Pigs. In a number of experiments on growing pigs (Berkshire) we have had many opportunities for studying the value of cod liver oil in stimulating growth and improving general condition, and have found from $\frac{1}{4}$ to 1 oz. daily is usually sufficient. There can be no doubt whatever as to its beneficial effects, whilst we have not yet come across a case in which the administration of the oil was not tolerated by the animal or was followed by undesirable consequences. Our experience has been that the pigs relish the oil and that it is particularly acceptable to the animals when they are not able to have access to pasturage and are

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receiving a diet tending to be deficient in the vitamin A. It seems unnecessary to enter into a discussion here as to the rôle of this vitamin in the formation of bony tissues, and its possible significance in rickets, so that we will content ourselves with saying that although we are convinced that pigs will not get rickets if they are receiving an adequate supply of the vitamin A in their diet we are not so certain that this disorder will develop if the reverse is true. (Zilva, Golding, Drummond and Coward (1921) (20), Golding, Zilva, Drummond and Coward (1922) (21).)

In our opinion the administration of cod liver oil of good quality in rather larger doses (i.e. $1\frac{1}{2}$ –2 oz. daily) is of great value to sows in pig and enables them to secrete a milk rich in vitamin A, and thereby give the young ones a good start in life.

In no single case have we had evidence of flavour or taint in the flesh or fat following the administration of cod liver oil to pigs, and it would appear to us that any such undesirable result is due to too high a dosage or perhaps to the employment of a very low grade oil. We have not ourselves observed taint in pigs, even when they were fed on a rather crude sample of oil, but in such cases it might be advisable to discontinue the administration of the oil some time prior to slaughter.

Cows. We have recently made an investigation of the value of cod liver oil in the winter feeding of cows and have obtained a certain amount of evidence that by thus supplementing the ordinary winter ration of hay, roots and concentrates, the concentration of vitamin A in the milk can be maintained at a high level, otherwise it tends to drop during the period of the deficient diet in winter. (Drummond, Coward, Golding, Mackintosh and Zilva (1923) (22).) Further experiments on these lines are now in progress which we hope will yield more conclusive evidence on this point. Certainly we found that the cows like the oil which was usually given in doses of $\frac{1}{2}$ –2 oz., and that no trace of taint or flavour came through to the milk even when the dosage was raised as high as 4 oz. As far as indicated by the limited data we obtained, the milk yield and fat percentage were unaffected by the supplement of oil. 2 oz. per day is the amount usually recommended for oxen and cows.

Calves. We have ourselves very slight experience of the value of cod liver oil in the rearing of calves, but such as it is it supports the generally favourable opinion expressed in the papers quoted in the introduction to this paper.

ADMINISTRATION OF COD LIVER OIL TO FARM STOCK.

Our experience leads us to advise the administration of the oil by direct means. The oil should be kept in a stoppered bottle or closed drum as it tends to lose its physiological action gradually by oxidation on long standing with exposure to air. This loss of potency can be roughly followed by the sulphuric acid reaction referred to above since the destruction of the vitamin A and the chromogenic substance by oxidation proceed in a somewhat parallel manner. An oil which has been in stock for some long time and which gives a poor response to the sulphuric acid test will probably have lost much of its specific action on the growth and the well-being of animals. It is a simple matter to have a dipper measure holding the required dose which can be filled and the oil poured over the animals' food. It can also be given separately, and we have found that pigs in particular like it given in this manner.

It seems advisable to sound a warning against the many attempts that will undoubtedly be made to place inferior grades of oil on the market, particularly in the form of special mixtures in which the dark colour and bad qualities of the oil will be masked by mixing it with other constituents. The use of such products, or false economy in buying the cheapest oils obtainable, may lead to disappointment and a revival of the old prejudices against what must be regarded as a most valuable foodstuff. Where practicable, therefore, it is advised that the oil be administered separately so that its quality can always be under control and that it be purchased directly from reliable manufacturers who will be prepared to guarantee their product.

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SUNFLOWER SILAGE.

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ONE of the main problems confronting the advocates of silage in this country is the selection of crops suitable for being grown for ensilage purposes, particularly in view of the fact that attempts to produce maize silage in this country have frequently been unsuccessful. It has been demonstrated, in trials extending over a number of years at Cambridge, that the mixed oat and tare crop can be used for the production of silage with success. The silage from oats and tares, when made under favourable circumstances, is possessed of great palatability and excellent nutritive value, and moreover, the process, considered from the point of view of losses of ingredients as a result of silo fermentation, is, if anything, more economical than that by which maize forage is converted into silage(1).

Other silage crops have been grown successfully in this country from seed mixtures including rye-grass, clover, sainfoin, lucerne, beans, etc., although much research is still necessary before accurate information can be secured as to the composition of the seed mixtures which yield the best results in the production of silage. Several factors must be taken into account in such investigations, such as suitability of climate, cost of seed, yield of crop per acre, time of maturing, the percentage losses suffered by the crop during fermentation, quality and feeding value of ensiled fodder, and so on.

The purpose of this communication is to give an account of a trial in which the sunflower crop was grown for storage in the silo. Sunflowers have been extensively cultivated in parts of America (mainly in the Pacific North-west), where maize cannot be grown successfully owing to unfavourable climatic conditions. The results of the scanty American trials on the subject of sunflower silage indicate that it possesses a good feeding value and provides an excellent substitute for maize silage where the latter cannot successfully be produced(2).

The sunflower possesses many characteristics desirable in a silage crop.

It is a hardy plant, capable of withstanding drought and frost. The process of seeding is relatively cheap, only 20-40 lb. per acre being required. It displays free, rapid growth on poor light soils and yields a heavy tonnage of green matter per acre. Its horizontally placed and broad leaves shade the ground, leading to a complete smothering of weeds, and facilitating, as a consequence, the cleaning of the land. Furthermore, it is an easy crop from the point of view of cutting, carting and chaffing for the silo.

Certain undesirable characters must also be recorded. The crop matures somewhat late in the season, and the stems of the plant are apt to be coarse and fibrous, although it is possible that the latter disadvantage may be to some extent overcome by modifying the methods of cultivation and by a proper selection of variety.

The variety of sunflower used in the experiment was Giant Ensilage. The crop was planted on a light gravel soil, after a crop of rye had been fed off, the date of sowing being June 13th, 1921. The land was dry at the time of planting, and the season of 1921 was exceptionally droughty. A little water was put in the seed furrows to ensure germination.

The resulting crop of sunflowers was in the main quite satisfactory and yielded at the rate of 20 tons of green matter to the acre, containing 18.5 % of dry matter, in spite of the droughty season in which it had been grown. A crop of maize grown at the same time yielded only 14 tons per acre, containing 17 % of dry matter. The oat and tare crop of the same year gave a yield of roughly 8-9 tons per acre, containing about 23.5 % of dry matter.

The crop was cut at 7 a.m. on October 11th, 1921, and was filled into the silo at 10 a.m. of the same day. At the time of cutting the greater part of the crop was in full flower; some flowers were over, but some buds had not opened. The stems in some cases were coarse and fibrous, but these were well disintegrated by the chaffing process, and the material looked promising as filled into the silo.

The procedure of filling was similar to that described in a previous communication(1), a small experimental wooden silo being used for the purpose. The experimental sample of chaffed sunflower was weighed into a large, loosely-woven jute bag, and this, together with a maximum thermometer, occupied a central position in the silo, being surrounded on every side by the compressed material. The top of the silo was sealed by means of a 15-inch layer of soil. During the weighing out of the experimental material, a representative sample was drawn from the bulk for analytical purposes.

The silo was opened on January 12th, 1922. Silage of good quality was encountered after the removal of a 2-inch layer of waste material. It was dark brown in colour and possessed a strong, yet pleasant smell, slightly reminiscent of the odour of the green crop. No odour of butyric acid could be detected. The flowers still retained their yellow colour and whole seeds of sunflower were present in the fodder. The thick parts of the stems possessed an outer coating of almost woody material, surrounding a moist sappy interior. The woody material had a very indigestible appearance and it seemed questionable whether stock would consume such portions.

The sample bag was encountered at a depth of 6 inches below the waste material; its contents were weighed and a representative sample was taken for analysis. The maximum thermometer registered 23° C.

Analysis of samples. The moisture content of the samples was determined in duplicate on representative samples weighing 200 gm., and the dried residue was ground up finely, air dried and submitted to complete analysis. In addition, 200 gm. samples were extracted with 500 c.c. distilled water by shaking in a machine for 4 hours. The extract was filtered successively through muslin and filter paper and 150 c.c. were made up to 500 c.c. with alcohol. The simple soluble constituents of the silage were then estimated by analysis of the alcoholic liquid. For a complete description of the analytical methods employed, the reader is referred to an earlier communication(1).

The following tables give the data obtained during the trial.

Table I. *Composition of green sunflower and sunflower silage*
(calculated on dry matter).

	Green sunflower	Sunflower silage
	%	%
Crude protein	11.28	12.12
Ether extract*	3.21	5.16
N-free extractives	54.91	49.14
Crude fibre	18.63	20.47
Ash	11.97	13.11
True protein	8.18	7.50
"Amides"	3.10	4.62
Pepsin-HCl soluble protein	7.30	7.40
Protein digestion coefficient (<i>in vitro</i>)	64.7	61.1

* Not taking into account volatile organic acids of silage.

Table II. *Showing changes in content of dry matter, volatile and non-volatile organic acids, amino acids and volatile bases undergone by sunflower crop during ensilage per 1000 gm. dry matter.*

				Green sunflower c.c. N	Sunflower silage c.c. N
Volatile organic acids ...	...	...	...	15.0	368.2
Non-volatile organic acids ...	...	...	...	45.5	998.9
Amino acids (with amides of asparagine type)				104.5	204.5
Volatile bases ...	...	...	...	12.0	95.1
Dry matter ...	...	...	...	1000 gm.	951.3 gm.

Loss of dry matter = 4.87 %.

Table III. *Constituents of silage extract expressed as percentage of dry silage.*

		%
Volatile organic acids ...	2.32	(calculated as acetic acid)
Non-volatile organic acids	9.45	(" " lactic ")
Amino acids ...	1.88	(" " crude protein)
Volatile bases ...	0.88	(" " crude protein)

Table IV. *Showing amounts of sunflower constituents in sample bag before and after ensiling, together with percentage gain or loss of constituents.*

	Green sunflower	Sunflower silage	% increase or loss
	oz.	oz.	
Moist material ...	419.0	390.0	- 6.9
Dry matter* ...	77.50	73.75	- 4.8
Organic matter* ...	68.23	64.28	- 5.8
Crude protein ...	8.74	8.75	+ 0.1
Ether extract* ...	2.49	5.26	+ 111.2
N-free extractives ...	42.56	35.49	- 16.6
Crude fibre ...	14.44	14.78	+ 2.3
Ash ...	9.27	9.47	+ 2.1
True protein ...	6.34	5.42	- 14.5
"Amides" ...	2.40	3.33	+ 38.7
Pepsin-HCl soluble protein	5.66	5.35	- 5.5

* Allowance made for silage volatile organic acids as acetic acid. Amount of silage dry matter in bag calculated as residue after drying at 100° C.: 72.23 oz.

DISCUSSION.

In considering the results set out in the above tables, the extremely non-homogeneous character of a flowering sunflower crop should be kept in mind, together with the consequent difficulty of drawing from a large bulk of chaffed sunflower a relatively small sample which, when analysed, gives an accurate idea of the composition of the main mass of the material. The same difficulty is encountered when sampling the mass of sunflower silage for analytical purposes. As a consequence, the analytical data are subject in some cases to appreciable experimental error, and it

is probably to this circumstance that the small gains of crude fibre and ash recorded as a result of ensilage are to be attributed. The crude fibre determination is especially liable to error as a result of sampling difficulties, owing to the extremely fibrous nature of the sunflower stems. In spite of these considerations, however, it is still possible to gain from the figures some insight into the type and amount of changes which have accompanied the conversion of the green crop into silage. In particular, the figures obtained in connection with the loss of dry matter can be relied on with a fair degree of confidence.

The sunflower crop as ensiled contained 18.50 % of dry matter and the resulting silage 18.91 % (including volatile organic acids calculated as acetic acid). An outstanding feature of the results is the extremely low percentage loss of dry matter which occurred during the ensilage of the sunflowers, namely 4.8 %. This is appreciably lower than any of the corresponding figures obtained in the ensilage trials with oats and tares(1), where the lowest recorded percentage loss of dry matter was 7.2 %.

The results tabulated in Table IV indicate that the absolute amount of crude protein underwent little or no change during ensilage. The amount of hydrolytic cleavage of true protein appears to be much smaller than that which was observed during the ensilage of oats and tares(1). The approximate figures are tabulated below for purposes of comparison.

	Green "fruity" oat and tare silage	Brown acidic oat and tare silage	Sunflower silage
Percentage loss of true protein	50	31	14.5
„ gain of "amides"	104	121	39

It is readily seen that the protein of sunflower is somewhat more stable during ensilage than that of oats and tares. This is further reflected in the values of the digestion coefficients of the two types of protein as measured *in vitro*.

Green sunflower protein	64.7 %
Green oats and tares protein	82.5 „

As a source of digestible protein, sunflower is obviously inferior to oats and tares.

It will be noted that the sunflower protein suffered a slight depression of digestibility during storage in the silo. This harmonises with previous observations on the ensilage of oats and tares and appears to be a

general feature of the changes which occur during ensilage of a green crop.

Roughly 17 % of the N-free extractives were destroyed during fermentation of the green crop, this leading to a large increase in the amount of ether soluble constituents, namely, 111 %. As with oat and tare silage, the non-volatile organic acids were present in excess of the volatile organic acids, although it should be pointed out that the figure for non-volatile acidity obtained in the titration of the silage extract cannot with justice be calculated wholly in terms of lactic acid. Evidence in support of this statement will be brought forward in another communication.

The conclusion arrived at during the investigation of oat and tare silage as to the possibility of the partial conversion of cellulose into N-free extractives during ensilage received no confirmation in this trial. It may be, however, that the woody nature of the cellulose of sunflower precludes the possibility of this change.

The palatability of sunflower silage was tested by means of a rough feeding trial with two-year old bullocks. When the fodder was first placed in the mangers, the cattle sniffed at it, but did not taste it. Three out of twenty-two ate it readily after 10 minutes and seven others tasted it. Eventually, the whole sample of 5 cwt. was consumed in the course of 3 days by the twenty-two bullocks.

The writers do not, from a consideration of the findings in this preliminary trial, feel prepared as yet to recommend the making of sunflower silage on a large scale for feeding to stock. It may be that different methods of cultivation (such as close planting) will lead to a desirable reduction in the fibrous nature of the stems. Tests should be carried out to determine the best variety of sunflower to be grown for silage; the digestibility of sunflower silage and its value as a feed for dairy cattle constitute further problems which require investigation before the practice of growing sunflowers for silage can be adopted widely in this country.

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THE SHAPE OF THE LACTATION CURVE.

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A PAPER⁽¹⁾ published recently gave the results of an investigation carried out on Milk Records obtained from the members of the Penrith (Cumberland and Westmorland) Milk Recording Society; the effects of the season of calving, of service, of age, and of the period of rest preceding calving, were studied and corrections for each of these factors were ascertained.

In the above paper mention was made of the very great variation of the shape of the lactation curve, due both to environmental conditions and to individual characteristics, and the present paper is the outcome of work done on the same data, with the object of studying how far the shape of the curve is due to the latter (genetic), and to what extent it is influenced by the former (environmental) causes.

SELECTION OF A FIGURE.

It was necessary to select a figure, by means of which the shape of each individual lactation curve could be given a definite numerical value.

From the mean lactation curves prepared it would appear that the total amount of milk given depends very largely on the length of the period during which the weekly yield lies between 100 and 200 lbs.; for moderate milkers the length of this period might give a suitable figure for our purpose, but for good milkers it would break down, as their yield is due rather to the period during which their yield lies between 200 and 300 lbs. per week.

The only alternative would appear to be some relation between the maximum and the total yield; such a figure would have the advantage of giving a means of testing the efficacy of the maximum yield as an indication of the genetic milk-producing value of the cow.

Table I gives the mean total yield and the mean maximum daily yield of cows calving in the various months of the year, and also the value of the factor (total/maximum) for each month (in this district).

Table I.

Month of calving	Mean total lactation yield lbs.	Mean maximum daily yield lbs.	age of
			$\frac{\text{total}}{\text{maximum}}$
January	5808	32.5	178.6
February	5169	31.1	166.2
March	5625	34.0	165.4
April	5420	35.2	154.0
May	5343	37.4	142.9
June	5384	37.1	145.1
July	5396	35.6	151.6
August	5949	32.0	185.6
September	5831	31.8	183.4
October	5677	29.8	190.5
November	6077	30.7	198.0
December	5604	30.5	183.7

It will be observed that the factor in the last column of the above table shows a gradual rise or fall from month to month—the totals being low in the spring and early summer months, when the maxima are high. For purposes of comparison, therefore, the ratio of the total to the maximum yield would be useless were no allowance made for the month of calving.

In view of the fact that it has been suggested that this factor (total/maximum) is nearly constant (200 with winter calvers and 180–190 with summer calvers⁽²⁾) it was decided to take the above ratio for each particular lactation and divide it by the mean ratio for the month of calving in which the lactation commenced (*i.e.* by the number given in the last column of Table I).

This gave a figure which varied, roughly, from 0.5 to 1.5, with a few extreme instances outside these limits. This figure has been called the *Shape Figure* (S.F.) of the lactation.

For example:—A January calver gives a maximum of 28.5 lbs. a day and a total of 6318 lbs. in the lactation.

Here the S.F. = $\frac{6318}{28.5} \times \frac{1}{178.6} = 1.24$, for as shown in Table I the mean ratio for January calvers is 178.6.

It will be noticed that the S.F. is high for a lactation in which the yield is maintained round about the maximum for a considerable period and only falls off slowly, whereas it is low when the curve gives a sharp peak and then falls off rapidly. It does, in fact, give a rough measure of the shape of the curve—high values being associated with curves that tend to be level.

The effect of the month of calving having been eliminated, the S.F. may possibly be affected by the following factors:

(1) Service Period (very largely). A short service period will not

usually affect the maximum, but will shorten the length of the lactation and lower the total yield considerably; *i.e.* a short service period will lower the S.F.

(2) Age. The ratio may possibly vary as the cow gets older.

(3) Dry Period. This may affect the maximum to a greater extent than the total or vice versa.

(4) Feeding, Weather, Conditions of Management, etc., which probably affect the total more than the maximum; these influences are, however, minimised for each individual whilst it remains in one herd.

INFLUENCE OF SERVICE PERIOD ON S.F.

A correlation between the length of the interval between calving and the next fertile service, and the S.F., showed that the latter rose as the former became longer—rising steeply at first and then more slowly, suggesting a curve of the form

$$y = A - Be^{-cx}.$$

The curve fitted is shown in Fig. 1 and will be seen to give a fair fit to the data.

Table II gives the S.F. associated with each service period at intervals of 20 days and the corrections to apply in order to eliminate the effect of service on the S.F. The standard service period has been chosen as 100 days—the mean of all the lactations obtained; the value of the S.F. given by the curve for this service period is 1.01.

Table II.

S.P. in days	Mean value of S.F. (from fitted curve)	Correction to S.F. for S.P. %	S.P. in days	Mean value of S.F. (from fitted curve)	Correction to S.F. for S.P. %
0-19	.82	+22	260-279	1.31	-24
20-39	.86	+16	280-299	1.34	-26
40-59	.91	+9	300-319	1.36	-27
60-79	.95	+5	320-339	1.39	-28
80-99	.99	+1	340-359	1.41	-29
100-119	1.03	-3	360-379	1.43	-30
120-139	1.07	-7	380-399	1.45	-31
140-159	1.11	-10	400-419	1.47	-32
160-179	1.15	-13	420-439	1.49	-33
180-199	1.18	-15	440-459	1.51	-34
200-219	1.21	-17	460-479	1.53	-35
220-239	1.25	-20	480-499	1.54	-35
240-259	1.28	-22			

VARIATION OF S.F.'s OF INDIVIDUAL COWS.

Having found corrections to apply to S.F.'s for the service period—the factor which would appear to have considerably the largest influence—it became possible to attack the question of whether the shape of a

cow's lactation curve is due entirely to environmental conditions or whether it is due partly to a genetic quality of the individual.

The cows selected for the work were all those of which the first three or more lactations were known, the following number being available:

Individuals with lactations 1-3 known—60 cows, *i.e.* 180 lactations

"	"	"	1-4	"	28	"	112	"
"	"	"	1-5	"	9	"	45	"
"	"	"	1-6	"	3	"	18	"
Total					100 cows with	355		"

The problem was attacked in two ways:

1st method. The standard deviation of all the 355 S.F.'s was compared with that of each one from the individual mean.

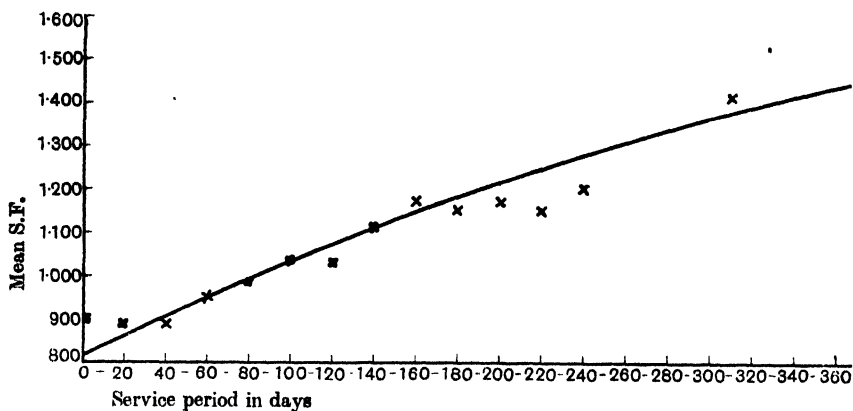


Figure 1. Variation of S.F.'s with service period.
1410 Lactations; correlation coefficient = $+0.495 \pm .013$.

That the latter is smaller would appear to indicate that individuals tend to have all their S.F.'s either large or small and not distributed evenly over the possible range—as would be the case did they depend entirely on environmental factors.

This method is open to the objection that a very large or small value affects the individual mean to a considerable extent, and so tends to lower its variation from that mean; but on the other hand it tends to make the deviations of the other S.F.'s of the individual higher.

2nd method. The 60 cows with 3 lactations were considered separately; the standard deviation of the S.F.'s of all the 180 lactations was found and divided by $\sqrt{3}$ —giving the standard deviation of the means of groups of 3 selected at random from the data. This was compared with the standard deviation of the mean S.F. of the 3 lactations of each

cow. That the latter is greater than the former indicates that each individual gives S.F.'s which do not fluctuate at random throughout the range, but tend to be grouped.

The 28 cows with 4 known lactations were considered in the same way.

Each method was applied to the S.F.'s uncorrected, and also when corrected for service period, with the results given in Table III; it will be seen that the differences when not actually significant approach significance in all cases, and they would appear, undoubtedly, to be real. It must be pointed out, however, that whilst allowance has been made for service, none has been made for feeding, management, etc.

In every case the result indicates that the S.F.'s of individuals tend to be grouped, that is to say, the shape of the lactation curve depends partly on a genetic characteristic of the cow.

Table III.
Comparison between variation of S.F.'s of individuals and those of all cows "lumped" together.

	Uncorrected S.F.'s			S.F.'s corrected for Service Period		
	Standard Deviation	Difference	Difference Its S. error	Standard Deviation	Difference	Difference Its S. error
1st method:						
{ S.F.'s of all 355 lactations...	$\cdot 224 \pm \cdot 0057$			$\cdot 189 \pm \cdot 0048$		
{ Variation of S.F.'s from individual means (355 lacta.) ...	$\cdot 147 \pm \cdot 0037$	$\cdot 077 \pm \cdot 0068$	7.6	$\cdot 122 \pm \cdot 0031$	$\cdot 067 \pm \cdot 0057$	8.0
2nd method:						
{ 60 cows with 3 lactations:						
{ Mean S.F.'s of 60 cows ...	$\cdot 160 \pm \cdot 0099$			$\cdot 133 \pm \cdot 0082$		
{ All S.F.'s (180) $\div \sqrt{3}$...	$\cdot 122 \pm \cdot 0043$	$\cdot 038 \pm \cdot 0108$	2.4	$\cdot 101 \pm \cdot 0036$	$\cdot 032 \pm \cdot 0090$	2.4
{ 28 cows with 4 lactations:						
{ Mean S.F.'s of 28 cows ...	$\cdot 183 \pm \cdot 0165$			$\cdot 169 \pm \cdot 0152$		
{ All S.F.'s (112) $\div \sqrt{4}$...	$\cdot 120 \pm \cdot 0054$	$\cdot 003 \pm \cdot 0174$	2.4	$\cdot 101 \pm \cdot 0046$	$\cdot 068 \pm \cdot 0159$	2.9

That the ratio of the total to the maximum, apart from the fluctuations caused by incidental factors, varies with the individual, detracts very seriously from the reliability of the maximum (as proposed by Gavin and Wilson or as used in the "7 day" tests in U.S.A.) when used as a measure of the genetic milk-producing value of a cow.

The following S.F.'s (corrected for service period) were given by two cows in their first 6 lactations:

P 390 1.12, 1.27, 1.12, 1.26, 1.33, 1.21

P 726 .99, .84, .91, .69, .66, .62

The value of P 390 would be considerably underestimated from her maximum yield, whilst that of P 726 would be greatly overestimated, the total yield in all cases being very low compared to her maximum.

VARIATION OF S.F. WITH AGE.

In view of the fact that the shape of the lactation curve is partly the consequence of a genetic factor, it was necessary when studying the variation of the S.F. with age, to compare the figures given by the same cows in successive lactations. All S.F.'s were first corrected for service period; then to find the variation from the 1st to the 2nd lactation all cows of which these two were known were included; similarly all cows of which the 2nd and 3rd lactations were known, were used to find the variation at this stage and so on. Table IV gives the results.

Table IV.

Lactations	Mean S.F.	Difference	<u>Difference</u> Its S. error	Number of lactations
1st	1.064 ± .008			
2nd	.943 ± .008	-.121 ± .011	7.1	253
2nd	1.000 ± .009			
3rd	.893 ± .009	-.017 ± .013	0.8	154
3rd	.986 ± .011			
4th	.987 ± .012	+.001 ± .016	0.0	99
4th	.985 ± .016			
5th	1.020 ± .018	+.035 ± .024	1.0	46
5th	1.055			
6th	.985	-.070		21
6th	1.019			
7th	.975	-.044		8
7th	1.019			
8th	1.062	+.043		8
8th	1.125			
9th	.975	-.150		2

It will be seen that there is a considerable drop (11 per cent.) in the S.F. as we go from the 1st to the 2nd lactation—a drop which is significant, being 7.1 times its standard error. In a table, published in the paper⁽¹⁾ mentioned at the beginning of the present one, it was shown that investigators working on maxima found a greater difference between the yields of 1st calvers and cows at their prime, than did investigators working on totals, and it was suggested that this was due to the lowering of the maximum yields of 1st calvers, heifers being unused to the act of milking. This suggestion is fully borne out by the above result—a reduced maximum of 1st calvers, relative to their yield, causing the S.F.'s of 1st lactations to be considerably higher than those of subsequent ones.

There is no significant change in the mean S.F.'s after the 2nd lactation; after the 5th lactation the numbers of cows available were very small and reliable results could not be expected. The general trend, however, after this stage, seems to be for S.F.'s to fall off slightly, *i.e.* at the approach of senility totals are lowered relative to maxima,

which would indicate that the falling of the milk yield after the cow has passed her prime, is not due so much to the physiological deterioration of the gland, as to nutritional and other factors.

EFFECT OF LENGTH OF DRY PERIOD ON S.F.

Fig. 2 shows the mean S.F.'s of all cows whose dry periods preceding the lactation under consideration fall in the various 20-day groups. The number of observations obtainable was 639; S.F.'s were first corrected for the length of the service period.

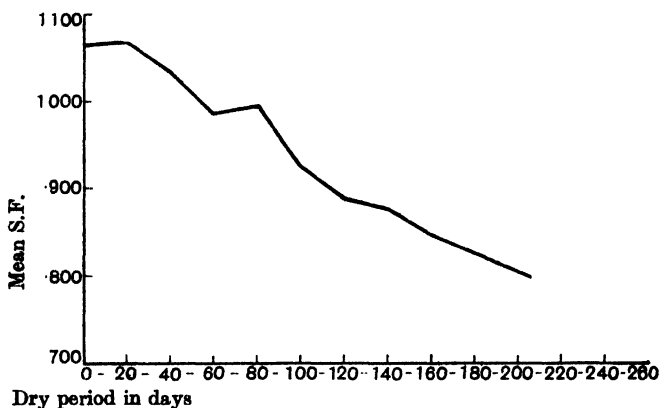


Figure 2. Variation of S.F.'s with dry period ("lumped" lactations). 639 Lactations; S.F.'s corrected for service period. Correlation coefficient = -0.348 ± 0.023 .

The ratio of total to maximum falls rapidly as the dry period before calving gets longer; that is, a short period of rest before calving is associated with a large S.F. This, however, is probably not a direct cause and effect; one short dry period is usually followed by another short one, which means that the cow milks longer than the normal time following the service period for which her figure has been corrected; this would obviously result in a high S.F. after correction. Hence it would be premature to deduce from Fig. 2 that S.F.'s are raised by short dry periods—*i.e.* that the maximum is lowered to a greater extent than the total.

In order, therefore, to obtain an idea of how the period of rest affects the subsequent S.F., we must compare the effects of different periods on the same cows. Denoting the periods 0-39 days, 40-79 days, and over 80 days, by *A*, *B* and *C*, comparisons were obtained between the effects of dry periods *A* and *B*, *B* and *C*, and *A* and *C*, on the subsequent S.F.'s of the same cows.

The results are shown in Table V and are seen to be absolutely contradictory. The relations *A-B* and *B-C* indicate that shorter dry periods are followed by higher S.F.'s—the differences, however, being less than their own standard errors—whilst the relation *A-C* gives a result in the opposite direction—the difference here being over three times its standard error.

The possibility of this contradictory result arises in the fact that in each of the relations in Table V different cows are involved.

Table V.

Dry period	Mean S.F.	Difference	Difference Its S. error	Number of lactations
<i>A</i>	$1.081 \pm .013$	$-.027 \pm .019$	.93	39
<i>B</i>	$1.054 \pm .014$			
<i>B</i>	$1.004 \pm .011$	$-.025 \pm .017$	.96	94
<i>C</i>	$.979 \pm .013$			
<i>A</i>	$1.024 \pm .017$	$+.104 \pm .022$	3.15	35
<i>C</i>	$1.128 \pm .014$			

When dealing with the effect of the dry period on the subsequent total yield, in the paper⁽¹⁾ previously referred to, it was found that a period of rest of less than 60 days considerably lowered the yield, whilst longer ones only raised it slightly. Accordingly the S.F.'s of individual cows having dry periods of less than, and more than, this critical period were compared; *i.e.* a cow has successive dry periods of 10, 78, 45 and 103 days preceding her 2nd, 3rd, 4th and 5th lactations; the mean of the S.F.'s of the 2nd and 4th lactations, was compared with that of the 3rd and 5th.

The number of cows obtainable for this was 58 and the result was as follows:

After dry period of under 60 days, mean S.F. = $1.021 \pm .013$

„ „ over „ „ = $1.059 \pm .013$

showing a rise of S.F. for longer dry periods of $.038 \pm .018$, *i.e.*

Difference = $1.36 \times$ its standard error.

This agrees with the relation *A-C* of Table V.

It has been shown that cows, when giving their maximum, lose body weight rapidly; if the dry period is regarded as being a time during which nutrition may be stored against this falling off, it would seem probable that short dry periods would affect the following lactation principally by lowering the maximum, *i.e.* would be followed by higher S.F.'s.

It can only be said from the present work that there is no confirmation of this, and that, if any conclusion could be drawn from such

divergent results as shown in Table V, it would be in the opposite direction—namely that a short period of rest preceding calving is followed by a lactation in which the total yield is lowered to a greater extent than is the maximum yield.

During the dry period fat, nitrogenous and other substances may be stored in the body, and, while during the period of maximum yield the amount of nitrogenous and other substances stored is probably the determining factor, yet the amount of fat may, by sparing carbohydrates, assist in the subsequent stages of the lactation. But before definite conclusions are formed on this point more material is required.

The fact that the S.F. decreases in a marked way with the dry period in "lumped lactations," but that when individuals are considered there is considerable doubt on the matter, would appear to afford further proof that the S.F. is an individual characteristic of the cow, of genetic significance.

S.F.'s OF HIGH AND LOW YIELDERS.

To compare the S.F.'s of high and low yielding cows, all those of which two or more lactations were known were included, the number available being 378. Lactation total yields were corrected for month of calving, service period, age and dry period and the mean of all known total yields of each individual was found. The cows were then divided into three groups—those giving a mean of less than 5000 lbs., those giving one between 5000 lbs. and 7000 lbs., and those giving one over 7000 lbs. The mean S.F.'s of all cows in each group are shown in Table VI; both the differences obtained are very large compared to their standard errors, and it seems to be a definite fact that low yielders give low S.F.'s and high yielders high ones.

Table VI.

Mean lactation yield	Mean S.F.	Difference (from mean above)	<u>Difference</u> Its S. error	Number of cows
Less than 5000 lbs.	$.784 \pm .012$	...	...	57
From 5000-7000 lbs.	$.923 \pm .006$	$+ .139 \pm .014$	6.95	171
Over 7000 lbs.	$1.069 \pm .006$	$+ .146 \pm .008$	11.23	151

This table explains the fact that the S.F. is due partly to an individual characteristic—it depending to some extent on whether the cow is a good or poor milker. It also indicates that the maximum yield does not vary from cow to cow to so large an extent as does the total yield (due probably to the maximum of the best milkers being limited by nutritional factors or to intra-alveolar pressure, determined by the intervals between milkings) and, finally, that by grading individuals

according to their maximum yields, the worth of poor cows is over-estimated, and that of good ones underestimated.

A high total is attained by a cow whose yield not only starts at a high level, but also remains round about the maximum for a considerable period, and it might be argued that this latter is determined by feeding, management, etc., or in other words that the small variation of the individual S.F. as opposed to that of "lumped" cows, is due entirely to the fact that the cow is in one herd all the time; *i.e.* that the variation of the S.F. is caused entirely by environmental factors.

As a means of obtaining a rough idea of how far the S.F. is dependent on these "management" causes, the mean S.F.'s were found of cows of the same herds, falling in the three "yield-groups" above.

The data contained the details of six herds in which there were 20, or more, cows of which more than one lactation was known. Table VII shows how the S.F.'s vary for each "yield-group" in each herd; the figures in the brackets give the numbers of cows which are included.

Table VII.

Herd	Cows with mean corrected lactation yield		
	less than 5000 lbs.	5000-7000 lbs.	over 7000 lbs.
<i>K</i>	1.090 (1)	.970 (10)	1.139 (15)
<i>L</i>	.910 (1)	.928 (6)	1.145 (13)
<i>N</i>	.772 (5)	.875 (11)	.991 (9)
<i>P</i>	1.000 (1)	1.011 (17)	1.122 (11)
<i>U</i>	.738 (13)	.866 (21)	1.045 (6)
<i>V</i>	.780 (3)	.936 (14)	1.028 (6)

The results seem perfectly definite, and show that, although from herd to herd there is considerable change in S.F.'s, yet, in every case, within the herd the S.F.'s show a marked rise from low to high yielders.

It would appear possible to arrange herds in order from the above table, showing those in which conditions and management are above the average and those in which they are below; in such a list herds *K* and *P* would appear near the top and herd *N* very low down.

The conclusion arrived at is, as suggested earlier in this paper, that although environmental causes affect the shape of the lactation curve to a large degree, there is yet an individual characteristic of each cow coming into play—this latter being that with heavy milkers the maximum does not bear so high a proportion to the total yield as with light milkers.

SUMMARY.

(1) The ratio of the total lactation yield to the maximum yield, divided by the mean ratio (in the particular district) for the month of calving in which the lactation commenced, has been selected to represent the shape of each individual cow's lactation curve, and has been called the shape figure (S.F.).

(2) The variation of individual S.F.'s was found to be less than that of all cows taken together—*i.e.* the shape of the curve, though largely determined by environmental factors, is due partly to a genetic characteristic of the cow.

(3) The S.F.'s of 1st calvers are high (about 11 per cent. above those of subsequent lactations); *i.e.* heifers give a small maximum relative to their total yield.

(4) No significant relation was found between the length of the dry period preceding calving, and the ratio of the total to the maximum yield in the subsequent lactation.

(5) S.F.'s rise markedly and definitely as we pass from low to moderate, and from moderate to high, yielders; *i.e.* in good milkers the maximum is lower relative to the total yield than in bad milkers. Though there is variation from herd to herd (due probably to the system of management), this rise was shown between bad and good cows within the same herd, and seems to be a definite genetic character.

The thanks of the writer are due to the members of the Penrith Milk Recording Society for the loan of their milk registers, and to Dr F. H. A. Marshall, Sc.D., F.R.S., and Mr G. Udny Yule, C.B.E., F.R.S., for much assistance. He is very greatly indebted to Mr J. Hammond, M.A., for constant help and many suggestions throughout the whole course of the work.

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- (2) GAVIN. "The Interpretation of Milk Records." *Journ. R.A.S.E.* 73, 1912. He quotes Wilson (*Proc. Royal Dublin Society*, June 1911) in support of the contention.

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THE COMPOSITION OF SECRETIONS OBTAINED FROM THE UDDERS OF HEIFERS DURING PREGNANCY.

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INTRODUCTION.

IN a recent communication [Woodman and Hammond, 1922(1)] it was shown that a secretion can be obtained in small quantities from the udders of virgin heifers, the amount showing considerable variation in different individuals. The secretion contains the characteristic proteins of colostrum, namely, caseinogen, lactalbumin and lactoglobulin, together with small amounts of fat, lactose and proteose. The conclusion was drawn that the initiation of mammary gland activity in the dairy cow is not necessarily dependent on pregnancy, but may be associated with the occurrence of the oestrous cycle. An extensive literature in regard to cases of milk secretion before pregnancy is quoted by Marshall(2).

The further question arose as to whether this activity of the gland proceeded without disturbance throughout the progress of pregnancy; or whether, on the other hand, the secretion underwent any marked changes in character and chemical composition. It seemed possible that an examination of the secretions obtained at different intervals during the progress of pregnancy might reveal the occurrence of such changes, and if this proved to be the case, it was of interest to know whether they were brought about abruptly or in a gradual manner, and whether they occurred periodically. It was also hoped that such a study might lead to the recognition of well defined stages in the development of the mammary gland and be of material assistance in the purely physiological study of the subject.

Unfortunately, circumstances arose which prevented the writers from carrying out their programme in its entirety; but though the results

which are brought forward in this communication are on that account somewhat incomplete, yet they are sufficiently noteworthy to warrant publication at this stage. A systematic investigation of the subject is at the present time being carried out in this Institute by Mr S. Asdell, B.A.

EXPERIMENTAL.

The animals under experiment were the same as those employed in the earlier work on the secretion from the udders of virgin heifers [Woodman and Hammond, 1922(1)]. They were all pregnant for the first time.

The main details of the analytical methods employed are as follows:

Total protein. Determined by Kjeldahl method. $N. \times 6.37 = \text{protein}$.

Caseinogen. Acidification of diluted fluid with acetic acid.

Globulin. Filtrate from previous determination neutralised and saturated with magnesium sulphate; precipitate filtered off and well washed with saturated magnesium sulphate solution.

Albumin. Filtrate and washings from globulin estimation acidified with acetic acid and placed in boiling water for a few minutes.

Fat. Paper coil method.

Lactose. Diluted fluid clarified by copper sulphate and sodium hydroxide solutions (Ritthausen method). Made up to known volume and sugar in aliquot portion determined by copper reduction method, using standard Soxhlet solutions. Identity of sugar confirmed by means of characteristic osazone.

The following table gives the results of the analysis of four secretions which were examined. The results are expressed as percentages by weight.

Number	1	2	3	4
Weeks pregnant ...	15	22	28	Last month
Treatment of animal	Secretions removed at intervals			Secretion not previously removed
Amount of secretion	45 c.c.	100 c.c.	350 c.c.*	80 c.c.
Specific gravity ...	1.026	1.110	1.030	1.060
Total solids	10.41%	40.80%	15.63%	24.68%
Ash	0.72	0.80	0.77	0.50
Fat	0.12	1.50	4.76	2.66
Total protein	8.07	37.90	7.61	20.31
Caseinogen	2.36	—†	4.02	2.58
Globulin	3.44	34.50	2.53	14.75
Albumin	1.61	1.00	0.49	1.57
Non-protein	0.66	1.90	0.57	1.41
Lactose	1.19	Trace	2.43	0.70

* The whole yield came from one quarter. Fluid not removed from remaining quarters.

† 0.5 % acetic acid insoluble protein (probably mucin).

182 *Secretions from Udders of Heifers during Pregnancy*

Secretion at the fifteenth week of pregnancy (previous secretions removed).

The data given in column 1 represent the analysis of a mixed secretion from three of the heifers; the sample was obtained on March 13, 1922. Two of the animals had been served on November 29, 1921, and the third on December 5, 1921, so that the secretion was obtained in the fifteenth week of pregnancy.

The bulk of the 45 c.c. came from one animal, the other two contributing 2 c.c. and 8 c.c. respectively. In appearance and chemical composition it did not differ materially from the secretions which had been obtained from the same heifers previous to service and during the first three weeks of pregnancy. The total solids were still lower than the value for normal milk, whilst fat was only present in traces and lactose to the extent of 1.19 per cent. The fluid was, relative to milk, rich in albuminoid matter, the globulin predominating in amount over the albumin and caseinogen. The ash content was about equal to that of normal milk.

The results indicate that the mammary gland was still displaying activity similar to that which characterised it in the early days of pregnancy. It is probable, therefore, that up to this point the character of the fluid obtainable from the udder had not been subject to any marked changes, although a more detailed investigation between the third and fifteenth weeks of pregnancy would be necessary before this could be asserted with absolute certainty.

Secretion at the twenty-second week of pregnancy (previous secretions removed).

A further sample of secretion was taken on May 2, 1922, from the udder of one of the heifers which had been served on November 29, 1921. The date thus represented twenty-two weeks from service.

It was at once apparent that the character of the secretion had undergone a very pronounced change since the previous milking on March 13. The fluid consisted of a thick viscous liquid of a honey-like consistency and was highly coloured by a yellow pigment, similar to, but darker than that of lymph or blood serum. The yield from the single heifer amounted to 100 c.c., a substantial increase above the amounts of secretion obtained at the earlier dates.

The fluid was neutral to both litmus and phenolphthalein and possessed the high specific gravity of 1.110. When a small portion was left exposed to the atmosphere, a film formed on the surface and ultimately the material dried to a horny mass.

On diluting the secretion with distilled water, a white flocculent precipitate settled out. This was filtered off and was found to be soluble in water containing a little salt. It was reprecipitated on pouring the saline solution into a large bulk of distilled water. This behaviour indicated the presence of an appreciable amount of globulin in the secretion.

When the undiluted fluid was heated in the water bath it set to a thick clot in about a minute. The diluted fluid also coagulated readily under the same conditions.

No flocculent precipitate was found to separate out when the diluted and filtered fluid was carefully acidified with very dilute acetic acid. A small quantity of material came out of solution by this treatment, but this remained undissolved after the addition of a large excess of acetic acid, and from its gelatinous, stringy appearance was thought to be mucin. It followed that the fluid probably contained traces of mucin but no caseinogen.

The results of the analysis of this sample are given in column 2. The secretion is characterised by an extremely high content of solids, namely 40.80 per cent. Of this, 37.90 per cent. consists of protein. The bulk of the protein, to the extent of 34.50 per cent., exists in the form of globulin, whilst the albumin remained at the low figure of 1 per cent. No part of the protein consisted of caseinogen.

The fluid forms an excellent starting point for the preparation of globulin, the latter being readily precipitated by ample dilution with distilled water.

An appreciable amount of fat (1.5 per cent.) was found to be present in the secretion. On saponification of the fat with alcoholic soda and acidification subsequent to removal of alcohol, only the faintest suggestion of butyric acid could be detected. It is therefore probable that the bulk of the fat contained in the honey-like secretion was not true milk fat.

In spite of the abnormally high percentage of total solids, the amount of mineral matter was not affected and still remained at the normally low value of 0.8 per cent. The composition of the ash was not investigated. In none of the secretions investigated did the ash figure show any tendency to vary much from the amount which is found in normal milk.

After removal of proteins, either by coagulation or by means of copper sulphate and alkali, the resulting liquid exhibited only a very slight reducing power when boiled with Fehling's solution for several

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minutes. Attempts to prepare a characteristic osazone were unsuccessful, and if lactose were present at all, it could only occur in the fluid in traces.

The fluid obtained from the heifer after twenty-two weeks of pregnancy is thus very sharply differentiated in character and composition from those obtained in the earlier stages. The composition of the early secretions afforded distinct evidence that the normal functions of the mammary gland were operating, even though feebly, at the time when the secretions were obtained. In the case of the honey-like secretion, which may substantially be regarded as a very concentrated solution of globulin, the absence of caseinogen and the presence of only traces of true milk fat and lactose indicate a cessation, at any rate for a time, of the processes which result in the production of the constituents of milk. The presence of globulin alone in a secretion is not necessarily a proof of synthetic activity on the part of the gland, since it is known that colostrum globulin is identical with serum globulin, and that therefore the presence of globulin in mammary secretions is explained by its transference unchanged from the blood stream. Lactalbumin and serum albumin are, however, different proteins, and in the absence of further evidence, it is impossible to decide whether the albumin of the honey-like secretion is the one or the other [Woodman(3), and Crowther and Raistrick(4)].

The abrupt change in the character of the secretion after about five months of pregnancy suggests that the mammary gland at this point has arrived at a well-defined stage in its development. Moreover, anatomical and histological investigation of the udders of heifers pregnant for the first time has shown considerable development of the alveoli at or about this time¹.

It may be that the above result is in some way correlated with the finding of Gavin [1913(5)] and confirmed by Hammond and Sanders [1923(6)], that the milk yield of pregnant cows begins to fall off rapidly about the twentieth week after service. Soon after service there is a slight decrease in the yield, but no marked drop occurs till the twentieth week, when the rate of fall is suddenly increased.

Further light was thrown on the question by the behaviour of another of the heifers, which gave, at a date corresponding with the twenty-second week of pregnancy, a yield of 10 c.c. of a secretion which consisted of a mixture of the honey-like material and the mobile fluid. Three of the quarters yielded the type of secretion obtained early in pregnancy, whilst the remaining quarter gave the new viscous secretion. This sample appears to mark a transitional stage and supports the view that the change in

¹ Details of this will be given in a communication in course of preparation.

the character of the secretion is brought about in a gradual manner and not as a result of a sudden disturbance.

Secretion at the twenty-eighth week of pregnancy (previous secretions removed).

The figures tabulated in column 3 refer to the analysis of a further sample of secretion obtained on June 12, 1922, from the heifer which gave the honey-like secretion, the analysis of which is given in column 2. The heifer had been pregnant about twenty-eight weeks. The whole of the sample was taken from the left hind quarter and amounted to 350 c.c. The quarter still contained more fluid and that contained in the remaining quarters was not removed.

The large increase in the yield of secretion from the udder of this heifer as compared with previous milkings denotes a marked increase in the activity of the gland at this stage. The fluid bore no resemblance to the honey-like material obtained in the preceding phase of the gland's development, but possessed the appearance of ordinary milk. On standing, a good thick cream came to the top.

A reference to the analytical results shows that the fluid resembles the secretions which characterised the virgin condition and the early stages of pregnancy. It contains all the characteristic constituents of colostrum. The content of dry matter, however, is higher (15.63 per cent.) and the fat, which was shown to be true milk fat, has risen to the high figure of 4.76 per cent. The amount of lactose (2.43 per cent.) is now roughly half the quantity found in milk, whilst the percentage of casein is appreciable (4.02 per cent.). The globulin content, however, is only 2.53 per cent., in marked contrast to the abnormally high percentage of globulin found in the honey-like secretion. The figure for the ash content was again at the normal value of 0.77 per cent.

It is clear, therefore, that the inactivity of the synthetic mechanism of the gland, which seems to be characteristic of the fifth month of pregnancy, is only of a temporary nature, if the products are removed; since after twenty-eight weeks of pregnancy, the gland not only is elaborating in appreciable amounts the constituents of milk, but is also yielding relatively large amounts of secretion.

Secretion in last month of pregnancy (no secretion removed previously).

The figures tabulated in column 4 are the results of an analysis carried out on a sample of fluid obtained from a heifer in first pregnancy due to calve about the middle of June 1922. The sample was obtained on May 25, 1922, so that the animal was in the last month of pregnancy.

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The yield of secretion amounted to 80 c.c.; this figure, however, cannot be compared with the yields previously recorded, since the animal was not one of the four originally under experiment, and it has been shown that individual heifers vary greatly in respect of the amount of secretion found in their udders.

This secretion was light brown in colour and distinctly viscous, though not nearly so viscous as the honey-like secretion previously described. Both in physical and chemical characters, it appears to mark a transitional stage between the occurrence of the honey-like secretion (column 2) and the colostrum-like phase (column 3). It resembles the honey-like material in its viscous nature, its high content of solids (24.68 per cent.) and protein (20.31 per cent.) and in the fact that the major part of the protein is present as globulin (14.75 per cent.). On the other hand, the presence of 2.66 per cent. of true milk fat, 2.58 per cent. of caseinogen and a small amount of lactose show its relation to the fluid of column 3.

It must be concluded that the entire removal of the honey-like secretion from the udder of the heifer after twenty-two weeks of pregnancy (column 2) had the effect of greatly speeding up the transition from the phase of mammary inactivity to mammary activity. The results in column 4 make it probable that if the honey-like secretion had been allowed to remain in the udder, then the change in the character of the secretion would have been much more gradual, extending over the whole period from five months after service to parturition.

In this connection, the results obtained by Hammond and Sanders⁽⁶⁾ are interesting, since they afford an indication that cows dry before the fifth month of pregnancy yield more milk in the subsequent lactation than those which are yielding milk well beyond the fifth month of pregnancy.

The low content of globulin in the secretion at twenty-eight weeks (column 3) is probably a result of the removal of the concentrated globulin solution found in the gland after twenty-two weeks of pregnancy. Had the latter secretion not been removed, it appears probable that, with the subsequent development of mammary activity, the fluid would have gradually taken on the normal character of colostrum, the percentage of globulin remaining high throughout. Support is given to this hypothesis by the fact that another heifer, which had not been previously milked during pregnancy, yielded at eight months a honey-like secretion from all quarters. It is also well known that the withdrawal of the fluid in the udder is necessary for the formation of milk. Starling⁽⁷⁾ states that in

women a fluid can generally be expressed from the nipples during the latter half of pregnancy, but that the secretion of true milk does not begin as a rule until the second or third day after parturition. The formation of milk may be anticipated, however, if a child has been put to the breasts during the latter part of pregnancy.

It will be noted that in the case of every secretion analysed, the protein globulin has been found present in appreciable amount. It is known that this protein is derived unchanged from the blood stream and further that during the normal lactation period, it only occurs in the milk in minute traces. It would thus seem that when the synthetic processes of the gland are operating at their maximum capacity, the transference of globulin from the blood stream to the milk secretion is inhibited. From the rapid rate at which globulin disappears from the mammary gland secretion after parturition, it would appear that the specific function of this protein is confined to the period of pregnancy. On the other hand, however, it is possible that globulin, during normal lactation, still continues to filter into the mammary secretion at a rate comparable with that during pregnancy, but that the great quantity of milk secreted during lactation has the effect of diluting it so considerably, that only traces of globulin can be found present.

In this regard, the following analyses are of interest. They represent the composition of secretions obtained from the udders of two non-pregnant cows which had been "dry" two and three months respectively.

		Cow "dry"	
		2 months	3 months
		%	%
Total solids	...	10.95	6.16
Ash	...	0.87	0.73
Fat	...	0.28	0.18
Total protein	...	9.30	4.54
Caseinogen...	...	2.58	1.57
Globulin...	...	3.00	1.11
Albumin...	...	2.30	1.08
Non-protein	...	1.42	0.78
Lactose	...	0.48	0.64
Specific gravity	...	1.026	1.015

It will be noted that true mammary activity is dying down and that the secretions again are characterised by an appreciable content of globulin. It seems as if the cessation of the production of milk (fat, caseinogen and lactose) by the gland cells result in the accumulation in the cistern and ducts of filtration products from the blood, which, when the gland is active, pass almost unnoticed in the secretion owing to the consequent great dilution.

FURTHER DISCUSSION OF RESULTS.

The results suggest that milk is formed mainly by the secreting activity of the gland cells (fat, lactose, caseinogen) and to a slight extent by filtration from the blood (globulin) since the amount of the latter undergoes an increase relative to the former when the secreting activity of the gland and the amount of secretion produced are low, *i.e.* after a cow is "dry" or during the growth phase of the gland. In cows suffering from acute forms of mastitis, which causes reduced flow, the milk frequently becomes yellow and colostrum-like, changing finally to a custard-like or honey-like secretion [Ernst(8)]. Anders(9) found that colostrum bodies were sometimes present in the milk of cows considerably advanced in lactation and also in the milk of cows with diseased udders.

It would appear that the formation of colostrum is not essentially connected with the period of parturition, and that it is a mixture of true milk with the secretion formed during the fifth and sixth months of pregnancy. Eckles and Palmer(10) have shown that abnormalities in the composition of colostrum are in direct relation to the length of time the cow was dry; if the cow is milked up to the time of parturition, the globulin secretion is removed from the udder, and under these conditions, where the cow is not dried off, Williams(11) has demonstrated that there is little or no change in the character of the milk after parturition. Engel(12) refers to the existence of two types of colostrum, a thick and a thin variety, the former of which contained 36.86 per cent. of coagulable protein, whilst the latter contained only 5.77 per cent.

The great variation found to occur in the composition of colostrum of cows [Frank-Albrecht(13)] is to be explained, in part at least, by the length of the dry period preceding parturition. Moreover, the rapidity with which the percentage of globulin falls in the first four milkings after calving [Grimmer(14)] suggests that this substance has accumulated in the udder during pregnancy. The percentage of globulin however sometimes remains fairly high for a few days, but this is probably due to the fact that the secretion of true milk is attaining its maximum more slowly than is usual. Ernst(8) states that in heifers calving for the first time the transition takes place more slowly than with old cows, although Engel and Dennemark(15) found no essential difference between the colostrum of first and successive lactation periods.

Porcher and Panisset(16) formulated the theory that colostrum is milk which has been retained in the udder, during which time the more soluble constituents tend to be reabsorbed and the colloids modified by

phagocytic action. Their conclusions were based on experiments in which sterile milk was injected into the peritoneum. Whilst this theory might hold with regard to the disappearance of lactose from the secretion, it seems difficult to account for the elimination of caseinogen in this way, as occurred with the heifer at the twenty-second week of pregnancy.

The extremely high globulin content of the honey-like secretion is not easily explained on the hypothesis that it results solely from filtration from the blood during a period when glandular activity is in abeyance. Oswald⁽¹⁷⁾ found, however, that during inflammation the permeability of the capillaries is increased, thus permitting large molecules like those of proteins to pass through more readily. The same effect has been shown to be brought about by lymphagogues of the first class (extract of mussels, oysters, etc.) [Starling⁽⁷⁾] and it is possible that the specific hormones developed in pregnancy may act in this way. Histological observation showed well-marked capillaries at this stage of development of the gland. The amount of protein in blood plasma, lymph and in various pathological oedemas [Wells⁽¹⁸⁾] is much below that in the secretion, so that considerable reabsorption of water would have to be assumed to account for the high protein content of the secretion. Even then it is difficult to understand why globulin accumulates to such an excessive amount, whereas serum albumin does not show any such tendency. In normal blood plasma the proportion of globulin to albumin is barely 2 : 1 whereas in the secretion it was 34 : 1. This would point to the specific utilisation of the albumin by the gland, possibly in the processes of cell development, the globulin not being utilised in this manner and thus accumulating in the ducts. Further work will be necessary, however, before this point can be settled.

The occurrence of the honey-like secretion will naturally not be noted with lactatory pregnant cows, owing to the dilution brought about by milk secretion. This may explain the conclusion drawn by Palmer and Eckles⁽¹⁹⁾ that gestation does not exert any direct effect on the composition of cow's milk, but that an indirect effect may be exerted in so far as pregnancy hastens the close of lactation. The latter circumstance is, in their opinion, the important factor involved in the changes in composition of the secretion. Craig⁽²⁰⁾, however, states that when abortion occurs before the fifth month, the secretion of milk is interrupted, whereas if it occurs in the latter half of pregnancy, the secretion of milk is established, although usually diminished. The experience of stockmen confirms this statement.

The very high globulin content of the honey-like secretion suggests

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a possible use for it in the preparation of concentrated antitoxins (against tuberculosis, abortion, etc.). The antitoxins contained in serum are known to be associated with the globulin fraction [Wells(18)] and this explains why antibodies are so easily passed into the colostrum and milk, and why colostrum has been found to be more potent than milk in immunization by suckling [Lane-Claypon(21)]. Famulener(22) found in some cases that the antitoxin content of colostrum was greater than that of serum itself. Immune bodies are also known to be more plentiful in the milk of cows suffering from mastitis and of cows in the later stages of lactation than in ordinary milk, and this is associated with the increased globulin content of the secretion under these conditions.

SUMMARY.

The initial work on the composition of the fluid obtained from the udders of virgin heifers has been extended and the character of the secretions of the mammary gland during first pregnancy has been investigated.

The results obtained point to the following conclusions:

During the first four or five months of pregnancy, the character and composition of the mammary secretion undergo no essential alterations. During this time, the mechanism of the gland which elaborates the normal constituents of milk is displaying feeble activity.

After about twenty weeks the secretion undergoes a progressive change in character and composition. The characteristic milk constituents begin to disappear, and ultimately the secretion, which is now honey-like in consistency, contains about 40 per cent. total solids, of which about 35 per cent. is globulin. During this phase, which apparently corresponds with a definite stage in the gland's development, the normal activity of the cells which results in the production of caseinogen, lactose, etc. seems to be in abeyance.

Removal of the honey-like secretion from the udder leads to a stimulation of normal mammary gland activity, in the same way as thorough and frequent milking stimulates activity during normal lactation. The viscous secretion gives way to a milk-like fluid. This is produced in relatively large amount and contains appreciable percentages of the normal colostrum constituents.

If the honey-like secretion is not removed from the gland, the transition from this phase to the colostrum phase appears to be much more gradual and is probably taking place uniformly throughout the remainder of pregnancy.

The secretions from the udders of "dry" cows were examined and found to resemble those obtained in the early stages of pregnancy. All the secretions analysed contained appreciable amounts of globulin, and the latter appears to be characteristic of mammary secretions taken outside the limits of normal lactation and to result from filtration and not true secretion.

The ash figure does not appear to be subject to much variation throughout the whole history of the gland. The percentage remains constant at about 0.7-0.8 per cent. The actual composition of the ash was not investigated.

It is suggested that the honey-like secretion may be found useful in the preparation of concentrated antitoxins.

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THE PRODUCTION, COMPOSITION AND UTILISATION OF WHEY.

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INTRODUCTION.

WHEY is the liquid which drains from the curd produced by the action of rennet on milk or from the curd formed by natural souring of milk or by the addition to milk of weak acids or other precipitants.

The concentration of cheese-making at factories in recent years has resulted in the production of large quantities of whey at centres where adequate provision has not been made for its disposal. Part of it is consumed as pig food. The remainder is discharged into streams and sewers. This involves the destruction of large amounts of valuable food material. To prevent contamination, discharge into streams is now generally prohibited. Sometimes it is irrigated on to the land as manure. On the farm practically all the whey produced is consumed as pig food.

Except on the lines indicated no attempt until recent years has been made in this country to exploit other outlets for factory whey. The problem is complicated by the fact that whey contains over 90 per cent. of its weight of water, it quickly decomposes and it is only produced in quantity during certain months of the year. A disposition to ignore the potential values of the milk sugar and other constituents which it contains further aggravates the position. The existence already in Great Britain of more than 350 milk factories—and the number is increasing—is a reminder that the matter is one not only of urgency but also of considerable magnitude.

For the above reasons and also in view of the fact that there is almost a complete absence of published data respecting the production, composition and utilisation of factory whey in the United Kingdom, it was decided to make whey a subject for investigation. The work was confined mainly to the collection of data which entailed a great many chemical analyses, numerous visits to factories, considerable correspondence, etc.

For convenience of treatment the subject is divided into three sections:—1. Production and waste. 2. Chemical composition, nutritive, manurial, market values, etc. 3. Utilisation.

SECTION I.

PRODUCTION AND WASTE.

Whey is not among the articles included in agricultural returns. Neither is any record kept of its production at farm and factory, but reliable data respecting the quantity of milk converted into cheese and

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of the weight of cheese made, are available. Attention was therefore directed to these sources of information.

The first point to be considered was the method of calculation of whey yields from milk data. In the manufacture of cheddar cheese¹ 100 gallons of milk on an average yields 100 lbs. of curd (green cheese) and 90 gallons of whey. The yield of whey, however, is subject to variation according to the composition of the milk and to the variety of cheese made. In addition certain losses occur during the process of manufacture, such as those caused by evaporation and waste from vats, tanks, etc., and according to the skill shown in the manipulation of the curd. For these reasons it was decided to obtain figures representative of conditions of manufacture at typical cheese factories.

Accordingly, arrangements were made to take, at regular intervals during the cheese making season, weights of milk, cheese and whey respectively, at two factories in Ayrshire and at the Dairy School, Kilmarnock. At the last weights were taken one day each week commencing in the month of March and continued until the month of September. At the two factories weighings were made on one day each month. The results obtained have been summarised and the average figures representative of each centre are shown below.

				Dairy School Mean of 17 weighings	Factory A Mean of 5 weighings	Factory B Mean of 5 weighings
Milk lbs.	...	...	...	600	3635	4354
Whey lbs.	...	...	...	518	3266	3858
Cheese lbs.	...	...	...	63.5	359.25	421
Cheese produced from milk	%			9.5	8.9	8.7
Whey	"	"	"	90.5	91.1	91.3
Loss of whey	%	"	...	3.5	3.1	2.0

Milk includes starter added in the proportion of 0.5 gallon to 100 gallons of milk and rennet extract at the rate of 1 oz. to 16 gallons of milk. Whey includes that obtained from the vat and cooler respectively, see p 208. Loss of whey was arrived at by deducting the weight of cheese and whey from that of the milk and the difference expressed as percentage of the latter.

From the above figures 100 lbs. of milk under the conditions of cheese making at the Dairy School yields 90.5 lbs. of whey; at Factory A, 91.1 lbs. and at Factory B, 91.3 lbs. Average 90.9 lbs. Deducting a mean loss of 3 per cent. the final figure is 88 lbs. From data received in reply to a circular letter posted to a number of cheese factories in the West of Scotland, asking for information on these lines, the average yield of whey worked out at 91.9 per cent. of the milk employed.

¹ For outline of manufacture see p. 200.

Turning next to the production of milk, figures taken from estimates supplied by the Ministry of Food¹ and from data abstracted from a census of the agricultural production of Scotland are tabulated below.

				1909-13	1918
England and Wales	...	...	...	1,044,652,000 galls.	No record available
Scotland	...	...	...	186,348,000	„
Great Britain	...	...	...	1,231,000,000	955,000,000 „ galls.

The decline in the yield of milk for 1918 compared with the 1913 average, was attributed mainly to a shortage of feeding stuffs brought about by the war. The yield has increased again, and the 1913 figures, in absence of more recent ones, have been taken as being as near an approximation to the present production, as it was possible to attain.

From the same source the quantity of milk used for cheese-making was also obtained. The figures are given below, also their equivalent in whey calculated on the basis already formulated.

				Milk 1909-13	Whey
England	...	...	...	70,400,000 galls.	63,400,000 galls.
Scotland	...	...	...	19,200,000 „	17,300,000 „
Great Britain	...	...	...	89,600,000 „	80,700,000 „

The proportion of milk converted into cheese in England works out at about 6·7 per cent. of the total milk produced, and in Scotland at about 10·3 per cent. The latter country, it is also estimated, produces about 22 per cent. of the cheese manufactured in Great Britain. Of this amount over 90 per cent.² is made in the nine Western and South-Western Counties. These Counties also provide over 50 per cent. of the milk produced in Scotland.

The foregoing figures provide a basis for arriving at an estimate of the magnitude of the subject under review.

Information was next required respecting the distribution of cheese-making between farm and factory. According to records of cheese-makers who operated under the British cheese distribution scheme during the period of control, the number of farms making cheese in the West and South-Western Counties of Scotland, including the Hebrides, was 760³. Other estimates supplied by cheese merchants put the number at 800⁴.

To obtain data respecting the cheese and whey production of individual farms a circular letter asking for the required information was

¹ Kindly supplied in correspondence in 1921.

² Census of Agricultural Production for Scotland, 1913.

³ Kindly supplied, in correspondence, by the Ministry of Food.

⁴ Messrs Andrew Clement and Sons, Glasgow, and Messrs John Templeton and Sons, Kilmarnock

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posted to 736 addresses. The replies received numbered 274. These were tabulated and a summary is set out below.

Average number of cows in herd	...	...	...	62
Average yield of milk per cow for cheese-making season only	...	...	...	461 galls.
Average yield of whey per day per farm	...	...	...	113 "
Average total yield of whey per farm per season	...	...	...	25,840 "
Average length of cheese-making season	...	...	...	227 days

Inspection of the tabulated results showed that the smallest herd consisted of 10 and the largest of 150 cows. The lowest average yield of milk per cow per cheese-making season was 232 gallons and the highest 800. The lowest average daily yield of whey per farm was 12 gallons and the highest 326. The smallest total yield per season per farm was 630 gallons and the highest 84,240. The shortest season was 60 days and the longest 325.

Of the 462 farms from which no information was obtained it is not possible to say what proportion dispose of their milk to factories. For this reason the figures given above have not been used as a basis for calculation of the total output of whey from farms.

As regards milk factories¹ no complete list of these was available and the information had to be obtained by correspondence. As a result there appears to be in existence 48, several are under construction and others are contemplated. Their distribution between different proprietors and counties is summarised as follows:

Proprietors:		%
Co-operative Dairy Farmers Associations	24	50.0
Scottish Wholesale Co-operative Society	7	14.6
United Creameries, Ltd. ...	4	8.3
Private companies and individuals	13	27.1
	Total 48	100.0

Counties of: Ayr 13, Wigtown 11, Aberdeen 5, Kirkcudbright 3, Dumfries 4, Lanark 3, Argyll 2. One each in Counties of Elgin, Inverness, Forfar, Perth, Stirling, Edinburgh, and Peebles.

The designation of each with date of erection is given in the list on p. 197.

The increase in recent years is confined principally to milk factories owned by Co-operative Dairy Farmers Associations, membership of which, it is claimed, carries with it substantial advantages not possessed by individual farmers².

¹ Milk depot, creamery or cheese factory; milk depot is a collecting and distributing centre; creamery was the designation applied to the first erected factories when butter and cream formed the principal articles produced. The term is now applied to a milk depot which is also a cheese factory.

² See p. 10. Report Scottish Agricultural Organisation Society, Ltd., Edinburgh, 1920.

*List of milk factories in Scotland. ****A. Affiliated with the Scottish Agricultural Organisation Society.**

County of	Name	Date of erection
Ayr	Rowallan Co-operative Dairy Farmers Assoc., Ltd.	1908
"	Kilmaurs " " " "	1909
"	Stewarton " " " "	1910
"	Dunlop " " " "	1908
"	Lugton " " " "	1908
"	Galston " " " "	1915
"	Fenwick " " " "	1911
"	Craigie and Symington " " " "	1919
"	Maybole and District " " " "	1920
"	Dalry " " " "	1919
"	South Ayrshire " " " "	1920
"	Lochilbo Road " " " "	1920
Dumfries	Upper Nithsdale " " " "	1919
"	Dunscore " " " "	1920
Kirkcudbright	Dalbeattie and District " " " "	1920
"	Stewartry " " " "	1921
Lanark	Lanark " " " "	1920
Wigtown	Galloway Creamery " " " "	1920
"	Port William " " " "	1920
"	Newton-Stewart " " " "	1922
Inverness	Inverness " " " "	1912
Stirling	Strathendrick " " " "	1920
Argyll	Netherloan Dairy Association—Clachan Seil	1916
Aberdeen	Aberdeen Dairy and Central Milk Depot	1917

B. Scottish Co-operative Wholesale Society, Ltd.

Lanark	Rylands	Strathaven	1909
"	East Kilbride		
Wigtown	Whithorn		1902
"	Bladnock		1899
"	Sandhead		1896
"	Stranraer		1891
"	Drummore		1901

C. United Creameries, Ltd.

Wigtown	Sorbie	1892
"	Tarf	1885
"	Colfin	1918
Argyll	Campbeltown	1919

D. Private Companies.

Ayr	Cumnock and District	1921
Peebles	Dolphinton	1920
Elgin	Elgin Creamery	1916
Perth	Perth " "	1899
Dundee	Carse of Gowrie	1906
Edinburgh	Edinburgh and Dumfriesshire Dairy Co., Ltd.	1891
Kirkcudbright	Dalbeattie Creamery	
Dumfries	Kyle " "	Dunscore
"	Annandale	Dumfries
Aberdeen	Reith Kennerty	Aberdeen
"	Coulter	"
"	Balgownie Dairy	"
"	Mellis and Son	Huntly

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The following summary of the dates of erection is interesting as showing the rate of progress in establishing milk factories in Scotland.

Up to 1907	...	...	12	27·9 %
1908-11...	...	...	8	18·6
1912-14...	...	...	1	2·3
1915-18...	...	...	5	11·7
1919-22...	...	...	17	39·5
Total			43	100·0

As already stated the primary function of a milk factory is to act as a centre for the collection and distribution of milk. The turnover in gallons of milk in 1920 for a number of factories is given in Table I below. The information was either abstracted from factory records, or acquired by correspondence, or taken from published balance sheets. Figures for those recently erected are excluded from the table.

Table I.
Milk turnover in 1920

Total gallons	Used in cheese-making gallons	Percentage used in cheese-making
504,789	230,762	45·7
896,229	278,759	31·1
640,000	90,000	14·1
563,557	52,300	9·3
468,102	159,895	34·2
1,132,594	573,301	50·5
500,000	29,320	5·8
534,332	146,210	27·4
482,025	311,227	64·6
600,000	100,000	16·6
360,000	260,000	72·2
600,000	400,000	66·6
665,107	205,479	30·9
662,000	422,704	63·8
1,121,942	615,599	54·9
585,841	9,480	1·6
517,742	465,346	89·8
910,000	606,667	66·6
665,725	150,897	22·7
756,958	412,538	54·5
310,000	45,000	14·5
400,000	120,000	30·0
Average 630,769	258,431	41·0

The largest turnover at any one centre amounted to 1,132,000 gallons and the smallest to 310,000, the average being over 600,000. It is calculated that about 29,000,000 gallons of milk pass through these distributing centres. The amount works out at about 17 per cent. of the total milk production for Scotland. Owing to the absence of figures

from some of the town factories with large turnovers, the estimate, in all probability, is below, rather than above, the actual figure.

The supply of milk in the summer months is greater than is required for consumption; the surplus is manufactured into cheese. The proportion manufactured into cheese by 22 factories is shown in Table I, page 198. The largest quantity employed for this purpose at any one factory was 615,000 gallons, the smallest 9,500, the average being 258,400. Expressed as percentages of the annual milk turnover, the proportion varied from 1·6 to 90·0, the average being 41·0. By correspondence it was learnt that in 1920 about 75 per cent. of the milk factories were making cheese.

Using the foregoing figures as a basis for calculation, the total volume of milk consumed in cheese-making at factories works out at about 9,300,000 gallons. The amount represents 48·0 per cent. of the total milk, including both farm and factory, employed in cheese-making in Scotland in 1920.

The factory cheese-making season as a rule extends from the month of March to the month of September. The shortest period for which records were obtained was 130 days and the longest 214, the average being 165 days. Only in certain circumstances was there surplus milk for cheese-making in winter. A few depots separate cream for butter-making.

Production of whey.

The yield of factory whey for 1920 is estimated to be as follows:

Average production per factory per season ...	232,600 gallons
Highest yield at any one factory per season ...	554,040 „
Lowest „ „ „ „ „ ...	8,500 „
Total yield of whey from factories in Scotland	8,372,000 „

The total production of whey in Scotland approximates to 17,300,000 gallons, which according to the above, is about equally divided between farm and factory.

Average daily yields of whey for season 1921 at four typical factories is shown in Table II, p. 200.

The figures are important inasmuch as they indicate the quantities for disposal daily at individual factories.

Waste of whey at factories.

A few factories run the whole of the whey to waste. The principal loss arises from the fact that at most of the factories whey is utilised as pig

Table II.

Average daily yield of whey in gallons at four factories.

January	1494	—	—	—
February	1538	—	604	—
March	2205	316	927	—
April	2988	1221	1116	27
May	3024	1053	1391	720
June	3204	1751	1593	832
July	2822	1800	1092	810
August	1478	1098	288	184
September	356	325	—	—
October	277	—	—	—
November	180	—	—	—
December	—	—	—	—
Proportion of milk made into cheese, % of total	50.5	27.4	31.1	9.3
Whey produced per season—gallons...	515,900	131,600	250,900	47,000

food, and that the pig accommodation is insufficient to deal in any way effectively with the whole of the whey produced. For example, as shown in figures, Table II above, the daily yield of whey from three to four months may be either 1000 or 3000 gallons. Assuming that a pig consumes from 3 to 4 gallons daily, it would require a herd of pigs of from 300 to 800 to dispose of it. With one or two exceptions the largest piggeries would not hold more than about 300 pigs. It follows therefore that during certain months more than one-half of the whey produced at many factories remains unconsumed.

SECTION II.

COMPOSITION AND PROPERTIES.

The next step in this investigation was to obtain data to show the composition of factory milk and whey and the extent to which both are subject to variation in the course of the cheese-making season. As already pointed out this was made necessary owing to the absence of data on the subject. As cheddar was the principal variety of cheese made, the work of this section was confined to a study of the whey produced from this source.

There are several stages in the process of manufacture and as each stage affects the composition and yield of whey, the following brief description of the process is given.

The first stage includes the "ripening," and the "coagulation" of milk. Ripening or souring consists in adding to the milk a culture¹ of

¹ A "starter."

a lactic-acid-producing-organism (*Streptococcus lacticus*, *B. bulgaricus*, etc.). The primary object is to convert milk sugar into lactic acid, temperature being a controlling factor. Theoretically milk sugar passes quantitatively to its equivalent in lactic acid, but small amounts of other products are produced. The acid dissolves part of the insoluble calcium compounds of the milk and produces a medium more favourable for the subsequent action of the rennet enzyme.

Coagulation is brought about by rennet added to the ripened milk. The rennet precipitates the casein which carries down most of the fat, part of the mineral constituents, and forms the curd or "coagulum." The serum or liquid portion constitutes the whey. The latter contains the milk sugar, albumen and other protein and non-protein nitrogen compounds not acted upon by rennet, along with the remainder of the inorganic constituents and of the fat. A concentration of about 0.22 per cent. of total acidity calculated in terms of lactic acid, a favourable temperature, a certain ratio of enzyme to volume of milk, and the presence of soluble calcium salts are conditions necessary to produce a suitable coagulation.

The second stage consists in cutting and scalding or "cooking" of the curd. The curd which is left in contact with the whey gradually hardens, due to the action, upon the physical condition of the protein, of acids, mineral salts and of heat. When sufficiently firm it is cut into small cubes and afterwards it is subjected to the operation of cooking and scalding. This consists in slowly raising the temperature until a maximum which is about 101° F. is reached, the primary object being to further stiffen up the curd. When a desired degree of hardness is attained¹, the bulk of the whey (vat whey, see p. 208) is drained off. During this stage slight peptic digestion of the curd occurs, and any soluble nitrogen products formed pass into the whey.

The third stage consists of "cheddaring" and milling the curd. By this is meant that the curd from which the bulk of the whey has been drained, is piled along each side of the cheese vat and allowed to cool slowly, drainage of whey meantime going on. During this operation the acidity of the whey increases up to between 0.75 and 0.85 per cent. and the peptic digestion continues. The combined effect of the treatment is to materially alter the texture of the curd; the aim being to produce a foliated structure. When this point is reached the curd is ready for milling and pressing. The yield of whey (cooler whey, see p. 208) is small, and the amount draining from the cheese press is still less.

¹ See also hot iron test in text books on Dairying.

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From the above brief description the general relationship between the composition of milk and the operations of cheese-making and the chemical content of whey should be manifest.

Different views are held with regard to the mechanism of the rennet action. But it is not intended here, either to enter into a discussion of these views, or to attempt to give a summary of the voluminous literature existing on the subject of milk and its constituents, except in so far as it affords an explanation of any point which arises in the course of the present work. Considerable confusion, however, exists in connection with the nomenclature of casein to which reference is now made.

From an historical stand-point it is of interest first to refer to the phraseology of milk constituents used by agricultural authorities in the early part of last century. The following example is typical of many recorded at that period¹. "Milk consists of three substances mixed together, namely the oily or butter-aceous, the lactic or caseous and the serous or whey." Liebig² refers to the principal protein of milk as casein or the cheesy matter and he does not differentiate between the casein in milk and that in curd. Hammersten³ distinguishes between milk casein and curd casein. He holds that the rennet enzyme acts directly upon the milk casein producing two substances, an insoluble curd, paracasein, and a soluble product, whey protein. He also showed that the change of casein to paracasein was independent of coagulation, the coagulation being due to the combination of paracasein with calcium to form an insoluble calcium paracasein (clot).

The nomenclature in general use in the United States and in Europe is as follows: casein is the uncombined casein molecule; calcium casein or caseinate is the compound present in milk and contains 1.5 per cent. of CaO ⁴. Paracasein is the product formed from calcium caseinate by the action of rennet, and it is soluble in water. Calcium paracasein or paracaseinate is insoluble in water and is the clot or curd protein.

By some investigators caseinogen is the name given to the unchanged casein compound in milk and which corresponds to calcium caseinate. Casein and dyscaseose are names given to the rennet curd. Caseose is the whey protein.

¹ *General view of the Agriculture of the County of Ayr*, by W. Aiton, 1811, p. 428.

² *Animal Chemistry*, by Baron Liebig, Pt. I. 3rd ed. 1846, p. 45; also by same author, *Familiar letters on Chemistry*, 1859, p. 373.

³ Hammersten, *Maly's Jahresb.* 1872, p. 118; 1874, p. 135; 1877, p. 158.

⁴ Solder, *Landw. Versuchs-stat.* 1888, 35, 351; see also basic calcium caseinate. Van Slyke and Hart, *Am. Chem. Journ.* 1905, 33, 461.

Method of experiment.

Samples of milk and the corresponding samples of whey from the vat and the cooler respectively were taken once a week from the Dairy School, commencing in the month of March and continuing until the month of September. Similar samples were taken monthly from factories A and B.

The method of sampling was as follows: The whey from the vat, for the purpose of weighing, was poured into a milk can. Each canful after weighing was sampled and the different samples added together. From the mixture one litre was taken for analysis. Milk samples were taken from the vats before renneting. The samples were conveyed to the Chemical Laboratory at the Dairy School for analysis. The determinations made in each sample include total nitrogen, fat, milk sugar, ash, specific gravity, acidity and total solids. Total nitrogen was determined by Kjeldahl's method; fat by the Gerber, and the sugar by the Polariscope (Schmidt and Haensch). Every precaution was taken to eliminate experimental errors.

In order to test the reliability of the method of sampling, duplicate samples were at first taken and analysed. The results of duplicate determinations were found to be in close agreement.

Factory milk.

The figures given in Tables III and IV show the average monthly composition of the milk delivered to the Dairy School and to two factories during the season 1921. The principal point of interest in these tables is the poor quality of the milk supplied to the two factories compared with that supplied to the Dairy School. The contrast is brought out prominently in Table V, p. 204, which gives the average composition of the milk for the season.

Table III.

Composition of milk (Dairy School).

		Monthly averages—percentages							
		March	April	May	June	July	August	September	Average
Water	...	87.89	87.78	87.74	87.43	87.56	87.31	87.62	87.6
Protein (total)	...	3.08	3.10	3.21	3.37	3.22	3.12	3.21	3.19
Fat	...	3.50	3.54	3.56	3.50	3.47	3.87	3.40	3.55
Milk sugar, ash, etc.	...	5.53	5.68	5.49	5.70	5.75	5.70	5.77	5.66
Total solids	...	12.11	12.32	12.26	12.57	12.44	12.69	12.38	12.40
Specific gravity	...	1.0310	1.0320	1.0320	1.0323	1.0321	1.0316	1.0321	1.0320
Acidity total	...	0.185	0.198	0.192	0.199	0.209	0.223	0.153	0.194
Acidity*	...	0.099	0.104	0.087	0.096	0.107	0.121	0.054	0.095

After addition of potassium oxalate.

Table IV.

Composition of milk.

Monthly averages—percentages

Factory A

	April	May	June	July	August	Average
Water	88.15	87.59	87.79	88.34	—	87.97
Protein (total) ...	3.01	3.31	3.16	2.89	—	3.09
Fat	3.10	3.20	3.19	2.80	—	3.07
Milk sugar, ash, etc.	5.74	5.90	5.86	5.97	—	5.87
Total solids	11.85	12.41	12.21	11.66	—	12.03
Specific gravity ...	1.0316	1.0329	1.0326	1.0320	—	1.0323
Acidity total	0.158	0.225	0.153	0.150	—	0.171
Acidity*	0.068	0.126	0.054	0.050	—	0.075

Factory B

Water	87.78	88.02	87.96	87.93	88.16	87.97
Protein (total) ...	3.14	3.31	3.08	2.82	3.01	3.07
Fat	3.25	3.00	3.15	3.20	3.30	3.18
Milk sugar, ash, etc.	5.83	5.67	5.81	6.05	5.53	5.78
Total solids	12.22	11.98	12.04	12.07	11.84	12.03
Specific gravity ...	1.0326	1.0332	1.0326	1.0316	1.0314	1.0323
Acidity total	0.180	0.153	0.203	0.216	0.171	0.184
Acidity*	0.090	0.050	0.104	0.122	0.081	0.089

* After addition of potassium oxalate.

Table V.

Average percentage composition of factory milk.

	Dairy School	Factory A	Factory B	Average
Water	87.57	87.97	87.97	87.83
Protein*	3.21	3.09	3.07	3.12
Fat	3.55	3.07	3.18	3.27
Milk sugar, ash, etc.	5.67	5.87	5.78	5.77
Total solids	12.43	12.03	12.03	12.16
Specific gravity ...	1.0320	1.0323	1.0323	1.0322
Acidity total	0.20	0.17	0.18	0.184
Acidity†	0.10	0.07	0.09	0.084

* Per cent. nitrogen $\times 6.38$.

† After addition of potassium oxalate. Acidity is expressed in terms of lactic acid.

Table VI.

Change in yield and composition of milk during lactation.

Month	Milk yield in lbs. daily	Total solids %	Milk fat %	Solids not fat %	Protein (total) % $N \times 6.38$	Specific gravity
April	32.1	12.37	3.5	8.87	3.18	1.0329
May	39.1	11.68	2.8	8.88	3.18	1.0318
June	34.8	12.25	3.3	8.95	3.24	1.0312
July	29.4	12.53	3.4	9.13	3.34	1.0315
August	26.6	12.63	3.5	9.13	3.58	1.0314
September	22.7	12.82	3.8	9.02	3.66	1.0311
October	19.1	13.38	4.3	9.08	3.88	1.0304

As a rule milk employed for cheese-making is from spring calving cows and as the season progresses it shows a gradual change in composition as a result of advancing lactation. The figures in Table VI¹, p. 204, illustrate the point.

Except in the milk supplied to the Dairy School there was no indication of any change similar to that shown in the above figures. The total solids in the factory milk were, if anything, lower at the end than at the commencement of the season. The summer was exceptional in that the rainfall was one of the lowest on record. However, season did not appear to affect the composition of the milk supplied to the Dairy School.

Comparisons were then made of the yields and of the fat content of morning and evening milk. Below are representative data for each. They were arrived at by averaging a large number of figures obtained in an experiment on the feeding of dairy cows².

			Morning	Evening
Milk yield lbs.	...	...	14.36	11.46
Fat %	...	...	3.36	3.80
Number of tests	...	...	896	896

The figures are confirmed by those of other investigators. It was afterwards found that at both factories morning milk only was made into cheese whilst at the Dairy School mixed morning and evening milk was employed. The foregoing data seem to explain satisfactorily the persistently low quality of the factory milk.

The ash of milk in the early part of the investigation was determined by direct ignition of the dry matter. Considerable difficulty was experienced in obtaining complete incineration and prolonged heating had to be resorted to. The results obtained were not consistent and the method was therefore modified, see ash, p. 212.

The average percentage of ash found was 0.71 per cent. Partial analysis of the ash gave the following average results expressed in percentages:

				Milk	Ash
CaO	...	...	...	0.167	22.8
P ₂ O ₅	...	...	...	0.219	30.1
MgO	...	...	...	0.021	2.9
K ₂ O	...	...	...	0.177	25.7

Season and stage of lactation affect the composition of the ash as shown in the following results which were obtained in samples of milk taken in the course of the summer.

¹ Berry, R. A., "Yield and Composition of Cow's Milk during Lactation," *Bull.* 76, *W. of Scot. Ag. Coll.* 1916, p. 71.

² Berry, R. A., "Wet and Dry feeding of Concentrates to Dairy Cows," *Journ. Ag. Sci.* 11, Pt. I, 1921.

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Table VII.

Percentages of mineral constituents in milk and milk ash.

	Milk			Ash	
	Ash	CaO	P ₂ O ₅	CaO	P ₂ O ₅
May 3rd, 1921	0.092	0.157	0.160	22.75	23.12
June 15th, 1921	0.099	0.150	0.186	21.42	26.54
July 5th, 1921	0.085	0.155	0.207	22.52	30.09
Average	0.092	0.154	0.184	22.23	26.58

The above figures show a tendency for the proportion of phosphoric acid in the ash to increase as the season advanced.

A table to show the extreme variation of milk constituents in samples taken at the three centres throughout the season has also been drawn up and the figures are contained in Table VIII below.

Table VIII.

Variation in composition of factory milk.

	Dairy School			Factory A			Factory B		
	Min.	Max.	Av.	Min.	Max.	Av.	Min.	Max.	Av.
Protein	3.02	3.50	3.26	2.89	3.31	3.10	2.81	3.31	3.06
Fat	3.35	3.95	3.55	2.80	3.20	3.07	3.00	3.30	3.18
Sugar	4.63	4.96	4.80	4.68	4.95	4.80	4.64	4.86	4.77
Total solids	11.85	12.82	12.43	11.65	12.41	12.03	11.84	12.22	12.03

The result is of interest inasmuch as it shows the variation in composition found in milk from herds.

Casein and albumen.

Since albumen is the principal protein in whey and casein is one of the chief factors in determining cheese yields, it was considered necessary to obtain figures showing the proportion of each of these compounds present in factory milk. For this purpose milk supplied to the Dairy School was employed. The amounts of each found at several periods are given below.

	Total protein	Casein	Albumen*
May 24th, 1921	3.30	2.79	0.51
July 5th, 1921	3.03	2.61	0.42
August 2nd, 1921	3.18	2.73	0.45
Average	3.17	2.71	0.46
May, 1922	2.93	2.36	0.57
"	2.98	2.43	0.55
Average	2.96	2.39	0.56

* Includes lacto-globulin, and any other nitrogen compound in milk.

The figures vary from those obtained by other authorities. For example, Koenig¹ found the following average amounts. Casein 3.0,

¹ Koenig, *Chemie der Mensch-Nahrung und Genussmittel*.

albumen 0.6 per cent. Stocking¹ states the limits of variation for each to be:

			Casein	Albumen
Maximum	...	...	6.29	1.44
Minimum	...	...	1.79	0.25
Mean	...	...	3.02	0.53

Total protein 3.55 %.

The figures quoted are for milk from mixed herds. It is however a well-known fact that the protein content of milk varies with different breeds of cows and according to the period of lactation. Van Slyke² states the protein and albumen content of milk of well-known breeds to be as follows:

			Casein	Albumen	Total protein
Holstein	...	...	2.20	0.64	2.84
Ayrshire	...	...	2.46	0.61	3.07
Holderness	...	...	2.63	0.69	3.32
Shorthorn	...	...	2.79	0.64	3.43
Devon	...	...	3.16	0.83	3.93
Guernsey	...	...	2.91	0.65	3.56
Jersey	...	...	3.03	0.65	3.68

As the results obtained in the present work are in accordance with those referred to above, it would appear that among the different breeds of cows, with one exception, the milk of the Ayrshire contains the lowest percentage of total protein. The effect of advancing lactation is to decrease the ratio of casein to albumen.

Whey.

For convenience the subject is considered under separate headings.

General properties. Fresh whey possesses a pale greenish yellow colour, slightly opalescent and varying with the amount of fat present. A yellow pigment (lactochrome) has been isolated from whey by Palmer and Coleridge³ which they state to be similar to urochrome, the natural colouring matter of urine. Lactochrome is a minor pigment to carotin, the chief colouring agent in milk.

In reference to colour the following quotation is suggestive⁴.

Go prick thy face and outrid thy fear
Thou lily-liver'd boy. What soldiers whey face?

The colour of milk is affected by the nature of the food, the carotin and xanthophyll constituents of which being the principal

¹ Stocking, *Manual of milk products*, 1920, p. 19.

² Van Slyke and Publow, *Science and Practice of cheese-making*, 1914, p. 173.

³ "Yellow pigment of milk and whey," Palmer and Coleridge, *Journ. Biochem.* **18**, p. 251.

⁴ Shakespeare, *Macbeth*, v. 3. 17.

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source. The author observed marked changes in the intensity of colour, especially in the fat of milk, as a result of substituting out-door for in-door feeding¹. Breed, age of animal, lactation period², etc. exercise but a slight influence on the colour of either milk or whey.

Like milk, whey possesses a characteristic odour. It is palatable and as judged by the following its consumption as human and cattle food dates back for a considerable period.

Down to the milk-house and drank three glasses of whey³.

“The whey is partly used as drink or made into a porridge with oatmeal which forms a wholesome, palatable and nutritious food. It is also fed to cows, horses and swine, much fine pork is raised from whey. The whey from three cows along with a very small supply of other food will raise a pig to a weight of between 10 and 20 stones from the months of April to December⁴.”

On standing, a thin layer of fat separates, and a small sediment of curd settles out. On estimation the latter amounted on an average to 0.02 per cent. The whey becomes increasingly acid owing to the action on the milk sugar of lactic acid organisms. With concentration of acid, albumen is precipitated, causing the whey to become lumpy (see p. 211). In course of time the albumen and other constituents undergo partial decomposition and the palatability and the nutritive value of the whey suffers. The acidity obtained as a result of a number of tests, of the whey in the tank at the Dairy School and as fed to pigs varied from 0.5 to 1.0 per cent. On boiling whey a flocculent precipitate of albumen separates.

Chemical composition. Below is a comparison of the composition of the whey draining from the vat and the cooler respectively. The figures given are the averages obtained for the three centres.

	Vat %	Cooler %
Water	93.17	92.83
Protein	0.87	0.94
Milk sugar	4.80	4.48
Fat	0.21	0.33
Ash	0.48	0.59
Undetermined* and loss ...	0.47	0.83
Total solids	6.83	7.17
Acidity	0.18	0.22
Number of analyses	27	27

* Principally organic acids and their salts.

¹ Berry, *Bull., W. of Scot. Ag. Coll.* 76, p. 57 *ibid*.

² Stocking, *Manual of Milk Products*, 1920, pp. 85-91.

³ Pepys' *Diary*, 11, 398.

⁴ Aiton, W., *A Treatise on Dairy Husbandry*, 1825, p. 140.

With the exception of the milk sugar, the percentage amounts of the other constituents in the whey from the vat were consistently lower compared with those obtained from the cooler. The difference, for reasons given on p. 201, was expected. In this connection attention is drawn to the fact that the liquid from the vat forms from 89 to 97 per cent. of cheese whey.

Before comparing the composition of the whey obtained from the three centres consideration is first given to each of the constituents and the extent to which each is subject to variation during the cheese-making season.

Constituents of whey.

Fat contributes towards the nutritive value of whey and can be separated as cream or it can be made into whey butter. As already pointed out, the amount passing from the milk into the whey largely depends upon the skill employed in regulating the conditions of cheese-making such as temperatures, acidity, etc., and in the cutting and in the manipulation of the curd. According to the figures shown below the fat content of whey is independent of the amount present in milk; a result which is in harmony with that obtained by other investigators.

			Dairy School	Factory A	Factory B	Average
			%	%	%	%
Milk	...	...	3.55	3.07	3.18	3.26
Whey	...	...	0.26	0.28	0.16	0.23

Combining the results obtained at the three centres the monthly limits of variation of the fat content found are given in Table IX.

Table IX.

Variation of fat in whey—percentages.

			Minimum	Maximum	Average	Milk average
April	...	...	0.12	0.29	0.20	3.36
May...	...	...	0.19	0.36	0.21	3.38
June	...	...	0.16	0.27	0.22	3.39
July	...	...	0.16	0.30	0.22	3.30
August	...	...	0.16	0.24	0.22	3.68

As shown in the foregoing figures whey may contain as low as 0.12 per cent. and as high as 0.36 per cent. This means that from 100 lbs. of milk made into cheese 0.11 to 0.33 lb. (equivalent to 0.12 and 0.36 per cent. fat in whey) of milk fat passes into the whey. Expressed in percentages it works out at from 4.7 to 8.1 per cent. of the fat in milk; the average being 6.5 per cent.

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The actual figures obtained for the three factories are as follows:

	Milk % *	Whey %	Percentage of total milk fat passing into whey
Dairy School	3.55	0.24	6.7
Factory A	3.07	0.25	8.1
" B	3.18	0.15	4.7
Average	3.26	0.21	6.5

The fat content of whey from Factory B was consistently lower than that from the other two. Fleischman and Van Slyke give the average percentage of fat in whey from whole milk cheese to be 0.35, Koenig 0.32, Smetham 0.24, Warrington 0.3, and Richmond 0.25, compared with an average of 0.23¹ in the present case.

Nitrogen compounds consist principally of albumen and to a small extent of a globulin and a caseose, along with any other nitrogen compound such as galactin, fibrin, etc. which are stated to be present in milk and are not coagulated by rennet. They contribute towards the nutritive value of whey. Commercially they are of importance in that they can be precipitated, dried and used as articles of commerce either as a food stuff or for certain technical purposes or made into whey cheese (see p. 233).

Albumen was determined in three samples of whey with the following average result:

Albumen	0.56 per cent.
Other forms of Nitrogen	0.31 „
Total	0.87 „

The average percentages of total protein in milk and whey at the three centres are shown below. Also, that of the proportion of milk protein passing into whey.

	Dairy School	Factory A	Factory B	Average
Milk	3.21	3.09	3.07	3.12
Whey	0.79	0.81	0.79	0.80
Milk protein {	24.6	26.2	25.7	25.50
Whey protein }				

These figures bring out the point that the total protein in whey at the three centres is fairly constant. Unlike fat the whey protein is not affected to the same extent by defective methods of manufacture. The monthly variations are shown in Table X, p. 211.

The divergence between the highest and the lowest figure amounted to 8.6 per cent. calculated on the lowest.

¹ Includes figures for months of March and September.

Table X.
Variation of protein in whey.

				Total protein in whey %		
Protein in milk %				Minimum	Maximum	Average
April	...	...	3.09	0.82	0.89	0.85
May	...	...	3.25	0.82	0.91	0.87
June	...	...	3.28	0.86	0.93	0.89
July	...	...	3.07	0.82	0.95	0.88
August	...	...	2.88	0.84	0.88	0.86

The protein content of whey given by different authorities is as follows: Smetham 0.88, Warrington 0.9, Koenig 0.86, Van Slyke 0.85, Fleischman 1.0 per cent. compared with an average of 0.87 per cent.¹ obtained in this investigation.

Milk sugar forms the largest and the principal constituent of whey. As already pointed out, certain organisms, under favourable conditions, rapidly convert it into lactic acid. Other decomposition products are formed depending upon the type of fermentation. The fact that the accumulation of fermentation products is inhibitive to bacterial growth was used as a basis for an experiment designed to show the length of time it was possible to store whey in tanks without undue deterioration.

The experiment was as follows: Whey was kept in a 24-litre carboy and was sampled and tested for acidity and milk sugar at first daily, afterwards at longer intervals. Temperatures were also recorded. The results are given in Table XI below.

Table XI.
Changes in composition of whey during storage.

Date	Number of days	Acidity %	Acidity in presence of potassium oxalate %	Sugar %	Average temperature ° F.
February 20th, 1922	0	0.14	0.11	4.94	58
" 21st "	1	0.45	0.43	4.61	58
" 22nd "	2	0.47	0.43	4.60	58
" 23rd "	3	0.47	0.43	4.55	59
" 24th "	4	0.47	0.44	4.55	55
" 27th "	7	0.48	0.45	4.56	52
March 7th "	15	0.48	0.44	4.39	50
" 29th "	37	0.45	0.38	4.09	49
April 12th "	51	0.46	0.40	3.90	50
" 26th "	65	0.52	0.46	3.53	51
May 3rd "	72	0.56	0.49	3.25	54
" 11th "	80	0.64	0.50	2.82	56

¹ Includes figures for months of March and September, see Table XIX, p. 218.

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In 80 days the milk sugar decreased from 4.94 to 2.82 per cent. After the first 24 hours the destruction of the sugar was slow but became pronounced towards the end of the test. The acceleration coincided with the appearance of moulds and with constant evolution of carbon dioxide gas. Almost from the commencement a scum collected on the surface, which consisted of albumen, and upon which moulds were soon found to be growing. From the variable odour evolved at different times from the whey it was evident that a series of fermentation changes were in progress. Acidity did not increase in proportion to the disappearance of the sugar. Ammonia was also produced. The experiment proved conclusively that it was not possible to store whey at least at a temperature of between 40° and 50° F. for any length of time without considerable deterioration.

The average percentages of sugar found in whey produced at the three centres were as follows:

Dairy School	...	...	4.78 per cent.
Factory A	...	...	4.76 "
" B	...	...	4.89 "
Average	...	...	4.81 "

The limits of variation are given in Table XII below.

Table XII.
Variation of sugar in whey.

			Sugar in whey %		
			Minimum	Maximum	Average
	...	Sugar in milk %			
April	...	4.86	4.62	4.88	4.71
May...	...	4.81	4.74	4.89	4.83
June	...	4.86	4.85	5.01	4.88
July	...	4.72	4.64	4.87	4.78
August	...	4.53	4.67	4.72	4.69

From this table the minimum amount found was 4.53 and the maximum 4.88 per cent. Age of whey as shown in Table XI, p. 211, is the factor which accounts principally for variation in sugar content.

Fleischman gives the average percentage of sugar in whey as 4.9, Koenig 4.8, Van Slyke 4.8 and Smetham 5.06.

Ash was determined by ignition of the dry matter and weighing the residue. Complete incineration by direct ignition was first made and as already pointed out the results obtained were not consistent. The dry matter was therefore charred, extracted with water, the residue burnt to ash. To this was added the filtrate, evaporated, ignited and weighed.

The average percentages of ash found in the whey at the three centres were as follows:

Dairy School	...	...	0.497 per cent.
Factory A	...	...	0.453 "
„ B	...	...	0.515 "
Average	...	...	0.488 "

The average of three determinations made in May 1922 was 0.53 per cent.

In the samples from the Dairy School the amount increased as the cheese-making season advanced. At the other centres there was a similar tendency though not so pronounced, see Table XX, p. 219. Vieth gives the percentage of ash in whey as 0.54, Koenig 0.65, Smetham 0.49 and Fleischman 0.60.

The limits of variation found in these experiments are shown in Table XIII.

Table XIII.
Variation of ash in whey.

				Ash in whey %		
				Minimum	Maximum	Average
April	...	...	...	.398	.539	.471
May	...	...	...	.384	.649	.472
June	...	...	...	.366	.547	.463
July	...	...	...	.433	.511	.478
August	...	...	...	.480	.574	.532

The minimum amount is 0.366 and the maximum 0.649 per cent.

Different views¹ are held as to the form of combination in which the inorganic constituents occur in milk and whey. The generally accepted view is that in fresh milk calcium exists in combination with casein, and in normal and acid salts of phosphoric and citric acids. Magnesium and potassium occur as salts of the same two acids, whilst the latter, along with sodium, are present as chloride. Richmond states that casein exists in milk in combination with both calcium and sodium. As to the physical condition of the inorganic components of milk, Van Slyke finds that the phosphates, namely the calcium and magnesium compounds, are partly in solution and partly in colloidal suspension. During souring of milk soluble lactates are produced from insoluble compounds of calcium.

As regards the distribution of mineral constituents between milk and

¹ Trunz *Zeit. für physiol.-Chem.* **40**, p. 263, 1902; Solder, *Landw. Versuchs-stat.* p. 351, 1888; Rona and Michaelis, *Biochem. Zeit.* **21**, p. 114, 1909; Van Slyke and Bosworth, *Journ. Biochem.* **20**, p. 135; Droop-Richmond, *Dairy Chem.* pp. 37 and 154, 1920.

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whey Richmond concludes that the bulk of the mineral salts pass into the whey. Van Slyke gives the proportion as 73 per cent. of the total mineral matter. Another estimate is that it amounts to three-quarters of the total¹. Of the phosphates of calcium it is stated that one-third only appears in the whey². In the present experiment it was found that 70.0 per cent. of the mineral constituents of milk passed into the whey.

Partial analyses of the ash were made with the following results:

			Whey	Ash
P_2O_5...	...	...	0.119	22.4
CaO...	...	...	0.066	12.5
MgO...	...	...	0.017	3.3
K_2O...	...	...	0.163	28.3

With advance of the lactation period slight increases in the amounts of lime and phosphoric acid occurred as shown in Table XIV below.

Table XIV.

Percentages of mineral constituents in whey and whey ash.

		Whey			Ash	
		Ash	CaO	P_2O_5	CaO	P_2O_5
May	3rd, 1921	0.560	0.060	0.108	10.63	19.28
June	15th "	0.538	0.063	0.112	11.77	20.71
July	5th "	0.564	0.069	0.116	12.67	20.26
Average		0.554	0.064	0.112	11.69	20.08

The proportion of mineral constituents of milk passing into the whey is: lime, CaO , 36.0 per cent.; phosphoric acid, P_2O_5 , 49.0 per cent.; magnesia, MgO , 75.0 per cent.; and potash, K_2O , 80.1 per cent.

Acidity was determined by titration with *N/9* caustic soda using phenol-phthalein as indicator. With this concentration one cubic centimetre of alkali is equivalent to 0.01 gram lactic acid, a convenient figure to use. The average figures for whey are shown in Table XV.

Table XV.

Acidity of whey expressed in terms of lactic acid.

	Dairy School		Factory A		Factory B	
	Total	After addition of potassium oxalate	Total	After addition of potassium oxalate	Total	After addition of potassium oxalate
April	—	—	0.167	0.129	—	—
May	0.172	0.130	0.212	0.154	0.308	0.240
June	0.168	0.123	0.236	0.152	0.198	0.149
July	0.205	0.157	0.150	0.108	0.162	0.124
August	0.190	0.152	0.144	0.103	0.223	0.171
September	0.149	0.113	0.182	0.129	—	—
Averages	0.177	0.135	0.182	0.129	0.223	0.171

¹ Manette and Musso, *Landw. Versuchs-stat.* **23**, p. 424.

² *Standard Encyclopedia of Modern Agriculture*, **12**, p. 153.

Fresh milk is amphoteric in reaction, a property attributed to the presence of acid phosphates and to casein¹. The acidity of fresh milk is partly due to the presence of these salts and to a less extent to carbonic acid and casein. In the titration of soluble phosphates such as disodium hydrogen phosphate which is neutral to phenol-phthalein, in presence of calcium salts, a di-calcium salt is formed. This compound immediately undergoes hydrolysis into calcium hydroxide and phosphoric acid, the former unites with more of the di-calcium salt and forms the tri-calcium salt. As a result of these changes it requires more alkali to make a solution of acid phosphates neutral to phenol-phthalein in presence of soluble calcium salts, than it does without². For this reason, the acidity of whey determined by the ordinary method, is high. To eliminate the error it is necessary before titration to remove soluble calcium salts by the addition of potassium oxalate. In the present experiment titrations were made both before and after the removal of these salts. Acidity of whey is due mainly to free lactic acid, also to acid salts and to carbonic and other acids.

Instead of caustic soda, lime water (calcium hydroxide), because of its cheapness, was tried. Also, being sparingly soluble in water, by having present an excess of undissolved hydroxide, a saturated solution at the ordinary temperature of the laboratory can easily be obtained. Saturated solutions prepared respectively from caustic lime obtained from 14 different sources gave a fairly uniform figure, namely, a concentration of about $N/20$. When preparing the solutions, in order to remove salts of the alkali metals which might be present, it was necessary to discard the first two saturated liquids made from the same sample of caustic lime. For this reason a large initial excess of lime was taken. Comparing the results of titrations using lime water and caustic soda respectively, it was found that more lime than soda was required to neutralise the same volume of either milk or whey, the figures for whey being 0.16 per cent. of acid determined by soda and 0.19 per cent. acid using lime water. The difference is again due to the formation and subsequent hydrolysis of acid soluble phosphates during titration. The difference diminishes with an increase in the amount of acid present and it disappears entirely when the titration takes place in presence of added calcium chloride as shown in the following determinations.

¹ Second Report on Colloid Chemistry, H.M.St.O. p. 101, 1919.

² "Cause of acidity in fresh milk of cows and a method for the determination of acidity," Van Slyke and Bosworth, *Journ. Biochem.* **19**, p. 73.

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NaOH	Ca(OH) ₂	NaOH CaCl ₂	Ca(OH) ₂ CaCl ₂
.13	.17	.22	.21
.16	.21	.25	.24
.38	.46	.48	.48
.48	.51	.52	.52

Since farmers find a difficulty in obtaining solutions of caustic soda of reliable strength for their acidity test, details of a method and apparatus using lime water is in process of being worked out.

In connection with acidity it is of interest to refer to the fact that during coagulation of milk by rennet the acidity falls appreciably as shown in the following figures¹.

Just before rennet action milk	Just after rennet action whey	% decrease
.16	.10	37.5
.20	.13	35.0
.30	.21	30.0
.40	.28	30.0
.55	.38	30.9

Richmond² attributes the fall as being due to the splitting off from the casein molecule of sodium, which passes into the whey and neutralises an equivalent amount of acid, the casein left being neutral. According to Van Dam³ there is no change in the hydrogen-ion concentration during the action of rennet, whilst Michaelis and Mendlessohn find that the time required for coagulation with acids is proportional to the hydron concentration. Other factors which influence acidity of milk and whey are—period of lactation, feeding and individuality⁴.

The acidity of whey is important inasmuch as it affects the value of whey as a food and as a source of milk sugar.

Specific gravity was determined at a temperature of 16° C. in a specific gravity bottle, of every sample of milk and whey examined. Average milk figures are given in Tables III and IV, pp. 203 and 204. A summary of the whey figures is given in Table XVI, p. 217.

Arithmetical relationships have been established between the constituents of whey, and formulas to represent these relationships have been worked out⁵. In an exhaustive examination of a number of samples of milk and whey Cochran⁶ found, for whey, that if the number repre-

¹ Berry, *Bull.* 76, *W. of Scot. Ag. Coll.* p. 62, 1916.

² Richmond, *Dairy Chemistry*, p. 55.

³ Van Dam, *Zeit. physiol. Chem.* 58, p. 295, 1908.

⁴ Berry, *Bull.* 76, p. 62, *loc. cit.*

⁵ Droop-Richmond, *Dairy Chemistry*, pp. 76–80, 1920.

⁶ Cochran, J., "Milk, skim milk and whey. A study of their composition and Specific Gravity," *Am. Chem. Soc.* 15, pp. 347–351, 1893.

sending the specific gravity above 1000 be divided by 4.25 the quotient = total solids.

Table XVI.

Specific gravity of whey.

			Specific gravity of milk	Specific gravity of whey		
				Dairy School	Factory A	Factory B
March	...	...	1.0310	1.0284	—	—
April	...	...	1.0320	1.0284	1.0283	1.0277
May	...	...	1.0320	1.0281	1.0282	1.0280
June	...	...	1.0323	1.0283	1.0282	1.0281
July	...	...	1.0321	1.0283	1.0279	1.0282
August	...	...	1.0316	1.0280	1.0274	—
September	...	...	1.0321	1.0279	—	—
Averages			1.0319	1.0282	1.0280	1.0280

The minimum and maximum figures along with the corresponding percentages of total solids found in the present experiments are as follows:

		Minimum	Maximum	Average
Specific gravity	...	1.0274	1.0286	1.0280
Total solids %	...	6.57	7.13	6.85

In whey, variations in the amount of milk sugar, which is the principal constituent, accounts mainly for differences in specific gravity.

Whey solid is the residue left after the evaporation of water. As already shown it is composed of those constituents, principally sugar and albumen, which are not retained in the curd formed by the action of rennet upon milk. For this reason it is possible to divide the constituents of milk roughly into cheese solids and whey solids. The division is not strictly accurate since a certain proportion of whey is always left in the curd and vice versa.

The average percentage of total solids in whey obtained at the three centres is as follows:

Dairy School	...	...	6.9	per cent.
Factory A	...	...	6.93	"
„ B	...	...	6.74	"
Average	...	...	6.86	"

At the Dairy School the whey solids were found to gradually increase with advance of the cheese-making season, while at the two factories the amount fell off towards the close of the season (see Table XX, p. 219). The figures are in agreement with the observations made in respect to the variation in milk constituents.

The monthly variations are shown in Table XVII, p. 218.

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Table XVII.

Total solids in whey—monthly variation.

			Percentages		
			Minimum	Maximum	Average
April ...	...	...	6.84	7.06	6.92
May ...	...	...	6.78	7.13	6.88
June ...	...	...	6.72	6.98	6.85
July ...	...	...	6.79	6.90	6.84
August ...	...	...	6.57	6.90	6.76

The limits of variation are 6.57 and 7.13 per cent. respectively.

The proportion of milk solids passing into the whey is shown in Table XVIII below.

Table XVIII.

			Total solids in milk	Total solids in whey	Whey solids % of milk solids
March ...	...	...	12.11	6.42	53.1
April ...	...	...	12.32	6.34	51.4
May ...	...	...	12.26	6.21	50.7
June ...	...	...	12.57	6.25	50.0
July ...	...	...	12.44	6.26	50.3
August ...	...	...	12.69	6.24	49.2
September ...	...	...	12.38	6.30	50.9
Averages			12.43	6.28	50.6

From this table it appears that, on an average, about 51 per cent. of the milk solids pass into the whey, the remainder are contained in the cheese.

Average composition of factory whey.

Seeing that the constituents of whey, through different causes, are subject to variation it is necessary now to consider what is the average composition of factory whey. Definite information on this point is essential when the question of utilisation of whey is under review. The average composition for the season, of whey produced at the three factories, is given in Table XIX below. The monthly averages are shown in Tables XX and XXI, p. 219.

Table XIX.

Average composition of whey in percentages.

		Dairy School	Factory A	Factory B	Average
Water ...	...	93.09	93.07	93.28	93.15
Protein ...	...	0.86	0.89	0.86	0.87
Fat ...	...	0.26	0.28	0.16	0.23
Milk sugar ...	...	4.78	4.76	4.80	4.78
Ash ...	...	0.49	0.45	0.52	0.49
Undetermined	...	0.50	0.55	0.40	0.49
Total solids	...	6.91	6.93	6.74	6.86
Specific gravity	...	1.0282	1.0281	1.0281	1.0281
Acidity total	...	0.18	0.22	0.18	0.19
Acidity*	...	0.13	0.17	0.13	0.14

* After addition of potassium oxalate

Table XX.
Composition of whey (Dairy School).

		Monthly averages—percentages							
		March	April	May	June	July	August	September	Average
Water	...	92.94	93.03	93.17	93.13	93.12	93.14	93.07	93.09
Protein (total)	...	0.907	0.843	0.856	0.895	0.850	0.869	0.914	0.876
Fat	...	0.27	0.25	0.23	0.22	0.31	0.23	0.28	0.26
Milk sugar	...	4.79	4.68	4.86	4.89	4.79	4.69	4.79	4.78
Ash	...	0.561	0.412	0.484	0.455	0.485	0.527	0.555	0.497
Undetermined*	...	0.532	0.785	0.400	0.410	0.445	0.544	0.391	0.497
Total solids	...	7.06	6.97	6.83	6.87	6.88	6.86	6.93	6.91
Specific gravity	...	1.0284	1.0283	1.0281	1.0283	1.0283	1.0280	1.0279	1.0282
Acidity total	...	—	—	0.172	0.168	0.205	0.190	0.149	0.177
Acidity†	...	—	—	0.130	0.123	0.157	0.152	0.113	0.135

* Principally organic acids and their salts.

† After addition of potassium oxalate.

Table XXI.
Composition of whey.

		Monthly averages—percentages					
		Factory A					
		April	May	June	July	August	Average
Water	...	93.12	92.87	93.30	93.2	—	93.07
Protein (total)	...	0.843	0.888	0.875	0.946	—	0.888
Fat	...	0.21	0.36	0.26	0.30	—	0.28
Milk sugar	...	4.62	4.74	4.90	4.77	—	4.76
Ash	...	0.510	0.403	0.412	0.486	—	0.453
Undetermined and loss*	...	0.697	0.739	0.453	0.298	—	0.549
Total solids	...	6.88	7.13	6.90	6.80	—	6.93
Specific gravity	...	1.0277	1.0285	1.0281	1.0282	—	1.0281
Acidity total	...	0.210	0.308	0.198	0.162	—	0.219
Acidity†	...	0.161	0.240	0.149	0.124	—	0.169

		Factory B					
		April	May	June	July	August	Average
Water	...	93.16	93.22	93.28	93.21	93.43	93.26
Protein (total)	...	0.888	0.875	0.875	0.856	0.843	0.867
Fat	...	0.12	0.19	0.16	0.16	0.16	0.16
Milk sugar	...	4.88	4.84	4.85	4.77	4.68	4.80
Ash	...	0.539	0.504	0.547	0.451	0.533	0.515
Undetermined and loss*	...	0.413	0.371	0.288	0.533	0.354	0.398
Total solids	...	6.84	6.78	6.72	6.79	6.57	6.74
Specific gravity	...	1.0283	1.0286	1.0282	1.0279	1.0274	1.0281
Acidity total	...	0.167	0.212	0.236	0.150	0.144	0.182
Acidity†	...	0.129	0.154	0.152	0.108	0.103	0.129

* Principally organic acids and their salts.

† After addition of potassium oxalate.

The feature of Table XIX is the closeness in composition of average factory whey. Apart from the variation in the fat which has been referred to, p. 209, the only other comment which appears to be necessary is the fact that the whey gradually becomes richer as the cheese-making season advances. For example the total solids, Table XX,

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increases from 6.83 in the month of May to 6.93 in the month of August. For variation in acidity and sugar see remarks, pp. 214 and 211.

Nutritive value of whey.

As already pointed out the principal outlet for whey in this country at the present time is as pig food. For this reason it is necessary to establish the value of whey for this or for similar purposes. As shown on the preceding page, over 50 per cent. of the milk solids are contained in the whey and they include practically all the sugar and the albumen of the milk, along with a little of the fat and a greater part of the mineral matter. These substances which form the whey solids are almost completely digestible. Moreover the whey protein, namely the albumen and the globulin, appear to be biologically identical with the bodies in the blood¹. Further as milk contains accessory food substances it is likely that some of these pass into the whey².

Reference has already been made to the opinions held by prominent agriculturists in the early part of last century respecting the value of whey for feeding purposes (p. 208). Since then a large number of trials have been made in this and other countries with the object of determining its feeding value. As a result of some of the more extensive of these trials the equivalent of whey, in terms of other food for producing live weight increase, was found to be as follows:

7.4	lbs. whole milk whey	= 1 lb. mixed meals	for pigs (1)
8.0	" "	= 1 " "	(2)
5.5	" mixed meal	= 1 " live weight increase	(3)
3.25	" barley meal	= 1 " "	(4)
4.2	" "	= 1 " pork	(4)
4.5	" "	= 1 " live weight increase	(5)
12.0	" whole milk whey	= 1 " barley meal	(6)
55	" " "	= 1 " live weight increase	(5)
2	" " "	= 1 " skim milk	(6)
4.4	" skim milk	= 1 " meal	(7)
10	" whey	= 1 " "	(8)

(1) *Bull. 225, Ontario Department of Ag.* p. 34, 1914.

(2) *8th Annual Report, Ag. Exp. Station Wisconsin*, p. 441, 1882.

(3) Henry, *Foods and Feeding*, p. 574.

(4) *Journ. Ministry of Agriculture*, 27, 4, p. 347, 1920.

(5) *Bull. 57, W. Scot. Ag. Coll.* pp. 220 and 270, 1911.

(6) Danish Expts. Copenhagen results.

(7) Average for Ontario, 3.5; Minnesota, 4.6; Utah, 4.3; Tennessee, 4.7; Wisconsin, 4.7.

(8) Snyder, *Dairy Chemistry*, p. 110, 1911.

Interpretation of the above data shows that about 50 lbs. of whey from whole milk cheese produces 1 lb. live weight increase in pigs. The

¹ Lane-Clayton, J. E., *Milk and its hygienic relations*, pp. 31 and 32, 1916.

² Hopkins, "Note on the Vitamine Content of Milk," *Bioch. J.* 14, 1920; Casimir Funk, "An attempt to estimate the Vitamine Fraction in Milk," *ibid.* 7, 1913, etc.

value will alter according to the actual food deficiencies of the rest of the diet, which the whey can supplement. Whey from separated milk cheese requires about 60 lbs. to give the same result.

The difference in feeding value between whey from whole milk compared with that from separated milk cheese is due to the absence of fat in the latter. According to Henry¹ the removal of fat from whey for the preparation of whey butter reduced the feeding value by about 25 per cent. Sammis considers that skimming of whey removes only about one-tenth of its feeding value². The reduction will obviously depend upon the initial fat content of the whey.

Fed alone to pigs up to an average of 6 gallons daily per pig an average live weight increase of 1 lb. per head per day was obtained³. Henry on the other hand found that pigs did not thrive on whey alone⁴. The author's experience is that when fed alone in anything like the quantity stated above it is laxative and liable to cause scouring. Apart from this effect whey is not a well balanced food as shown in the average analysis on p. 218. It is poor in protein. In consequence it is best fed along with suitable meals to supply the protein deficiency. In the Kilmarnock experiments 2 lbs. of meal to 2½ gallons of whey was found to be a suitable proportion for adult animals. Replies received from a circular letter dispatched to cheese farmers in the West of Scotland asking for information as to their experience upon this point is summarised below:

Number of farms	Weight of pigs stones	Number of pigs	Ratio of whey to meal lbs.
2	4	80	14 whey: 1 meal
41	5-10	224	7 " 1 "
32	11-15	281	5 " 1 "
11	15-20	268	5.7 " 1 "
Totals 86		853	

When made into a mash with whey, chemical changes affecting the digestibility of the meal appear to occur, a point which is under investigation. According to the experience of bacon curers a certain proportion of whey in the diet of a pig improves the quality of the bacon.

That whey possesses a food value over and above that supplied by the protein, the fat and the carbohydrates was observed by Henry in 1891. He states that whey increases the availability of the ration by

¹ *Bull.* 225, Ontario Dept. Ag. p. 34, 1914.

² Sammis, *Cheese-making*, p. 29, 1918.

³ *Bull.* 57, W. of Scot. Ag. Coll. p. 268, 1911.

⁴ 8th Annual Report, Wisconsin Expt. Station, p. 47, 1891.

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more than the solids it contains. Further, good results were obtained by feeding barley and whey together. While whey is poor in protein, the protein which it contains provides a useful supplement to the protein of barley¹. It was also found that whey and barley or maize were an excellent food for fattening adult pigs, but as a food for young pigs it was deficient in protein. In a series of experiments by the author² carried out with the object of determining the experimental error in pig-feeding trials, in which whey was used, the variable and somewhat remarkable increases produced by incrementing the quantity of whey consumed, could not be accounted for by the nutrition values of the known whey solids. The increases may be due to the protein of the whey supplying a deficiency in the protein metabolism of the rest of the diet, such as it appears to do when consumed along with barley; or to the presence of accessory food substances which are otherwise wanting or are below the minimum requirements; or lastly it may be due to some influence of the inorganic constituents of the whey.

Golding finds that whey is deficient in fat soluble vitamin A. According to McCallum and Davies³ whey from which albumen has been removed by coagulation can be kept at the boiling point for six hours without any appreciable loss in its nutritive activity in so far as the water soluble accessory food substances are concerned.

Whey is used for infant feeding⁴ and for dietetic purposes⁵. It is now on the market in the form of a powder⁶, having the following composition:

Moisture	...	...	...	...	1.20
Fat	...	...	...	...	0.27
Protein	...	...	...	...	14.25
Soluble carbohydrate	...	...	...	...	74.45
Ash	...	...	...	...	9.83

The condition of the whey, whether fresh or stale, influences its feeding value (see p. 211). Kellner⁷ states that it is advisable to feed

¹ *Bull.* 319, *Wisconsin Exp. Station*, p. 71, 1920.

² Berry, R. A. and O'Brien, D. G., "Errors in feeding experiments with cross-bred pigs," *Journ. Ag. Sc.* 11, Pt. III, July, 1921.

³ *Journ. Biochem.* 23, p. 249, 1915.

⁴ Bosworth, A. M., "Whey in infant feeding," *Am. Journ. diseased children*, 9, p. 2, 1916. Giffhorn, H., "Feeding of children on whey food," *Jahrb. Kinderheilk.* 77, pp. 635-639, 1914. Food Products from Whey, Process of producing, Ramage, A. S., U.S. Pat. 735,148, 1903.

⁵ Whey utilisation for dietetic purposes, Bond, Eng. Pat. 23127, Oct. 1909.

⁶ Casein, Ltd., Battersea, London.

⁷ Kellner, *Scientific Feeding of Animals*, p. 220, 1909.

why in a boiled condition and that sour whey is unsuitable for pigs with a delicate digestion. But by using sour and sweet whey respectively in some pig-feeding experiments carried out by the Ontario Agricultural College no difference was found. The whey used by the author in pig-feeding experiments at Kilmarnock contained from 0.5 to 1.0 per cent. of total acidity. The higher figure was obtained in the summer months.

Compared with succulent crops for pigs, whey was found to be slightly superior in feeding value to that of turnips¹. An opposite result to this was, however, obtained in a number of trials carried out at the Experiment Stations of Ohio, Montana, Utah and Ontario, where 5.7 lbs. of roots was found to be equivalent to 1 lb. of meal for producing live weight increase. This works out to a ratio of 1.5 lbs. whey to 1 lb. pulped roots. The results obtained at individual stations varied. For calf feeding 1 lb. whey was found to be equal to $\frac{1}{2}$ lb. of skimmed milk² which agrees with the figure for pigs. For cows, given at the rate of one gallon per day, it was found to exercise a favourable influence on the yield and quality of milk³. As poultry food⁴ excellent results have been obtained both for egg-laying and for fattening. For feeding bees whey is recommended in the following proportions:

Boiling water	...	...	225 grms.
Fresh whey	...	...	225 „
Cane sugar	...	...	400 „
Honey	...	...	140 „
Phoenix syrup	...	...	10 „
Total 1000			

The *Market value* of whey varies according to the local demand for pig feeding and to the quantity produced daily. Where the production is greatly in excess of the demand or when it is not consumed at the factory as pig food, it can be procured for the cost of carting. Replies received from factories in answer to a query asking for the current market price obtainable for whey in 1921 included the following prices per gallon: $\frac{1}{4}d.$, $\frac{1}{2}d.$, $\frac{3}{4}d.$, $1d.$, $1\frac{1}{2}d.$. The pre-war value placed upon whey at the Dairy School was $\frac{1}{2}d.$ per gallon, a figure also quoted in 1916⁵. Van Slyke puts its pre-war value at from 8 to 10 cents per 100 lbs. for feeding and from 6 to 7 cents for the extraction of sugar.

¹ *Report 30, Wisconsin Ag. Exp. Station, 1895.*

² *Graef-Milch-Zeitung*, p. 183, 1880.

³ *Schrodt, Jahresb. J. Ag. Chemie*, p. 441, 1882.

⁴ *L'Industrie laitière*, Paris, 47, pp. 757-759, 1910.

⁵ *Journ. Bd. of Ag. and Fisheries*, Supplement 16, p. 24, 1916.

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Manure value.

The value of whey for manurial purposes is derived from the nitrogenous and the inorganic constituents. The former, before assimilation by plants, require to undergo change in the soil to the nitrate condition. The average percentage composition is as follows:

Nitrogen	...	...	...	0.13 per cent.
P ₂ O ₅...	...	...	...	0.12 "
K ₂ O...	...	...	...	0.16 "
CaO...	...	...	...	0.07 "

The sugar is a source of energy for soil organisms.

As already pointed out on p. 193, a few of the factories in the past year were spraying whey from a water-cart on to permanent pasture. The result was favourable but the carting made the cost excessive. In Ireland at, at least, one factory, namely that of the Ardagh Co-operative Society¹, whey is irrigated on to pasture fields from the month of June to September at the rate of 1000 gallons per two acres per day, and the pasturage is used for grazing. The practice has been carried on for several years on the same field and the effect appears to be to encourage coarser grasses. Applied at the rate of 2000 gallons daily per acre on another field the pasturage became unfit for grazing. The soil was used as a filter bed. But in this case the whey was first drained through peat to remove suspended solids and the spent peat afterwards used as manure. Whey is boiled to precipitate albumen, which is skimmed off and employed for making compost.

With the object of testing the value of whey for manurial purposes field and pot experiments were carried out at the Experiment Station, Kilmarnock in the summer of 1921.

Pot experiments. Oats and rape. Poor sandy soil from Gargirston, Kilmarnock was used. The scheme, which is shown below, was carried out in duplicate.

Treatment						Weight of oat crop dry
Pot 1.	Untreated	...	...	...	...	177.0 grms.
" 2.	Complete manure	...	...	...	...	432.5 "
" 3.	Whey	...	...	...	...	291.5 "
" 4.	" neutralised with lime and clear liquid used	...	...	...	...	325.5 "
" 5.	" + carbonate of lime added to soil	...	...	...	...	360.7 "

The complete manure was applied at the rate per acre of 1½ cwts. of nitrate of soda, 2½ cwts. of superphosphate of lime, and ¾ cwt. of sulphate of potash. The whey added contained nitrogen equal to that

¹ *Ninth Annual Report, Royal Commission on Sewage*, p. 93, 1915.

supplied in pot 2. It was added in three applications, an equal volume of water being supplied to the pots receiving no whey. Acidity of whey 0.84, 0.86, 0.96 per cent., nitrogen content of whey 0.13 per cent. Weight of soil in pot 40 lbs.

The seed was sown on 26th May and the crop cut and weighed on August 6th, 1921.

The rape was damaged by wind and rain and the weights were unreliable. A similar scheme of experiments with oats and rape was carried out in the field. The crops were, unfortunately, damaged by the weather and were not weighed.

The conclusion arrived at from the results of these experiments is that whey possesses definite manurial properties. Previous neutralisation or application of suitable quantities of limestone to the soil adds to the value of these properties.

SECTION III.

UTILISATION.

There are two principal outlets for whey, namely, (1) as pig food and (2) as a source of milk sugar. This section is devoted mainly to their consideration.

Pig food.

It is evident from the data contained in the two foregoing sections that the problem in connection with the disposal of whey as pig food is primarily an economic one. It has been shown that whey is a cheap, easily digestible and nutritious food. But it possesses certain disadvantages; it rapidly ferments and deteriorates in value; over 90 per cent. of its weight is water, which adds greatly to the cost of transport. Further, and as a rule, it is produced during spring and summer months only, the average factory season extending to 165 days. However, when the supplies of whey cease suitable foods are available as substitutes, a fact which to a large extent counterbalances any disadvantages caused by the stoppage of the whey supplies. That there is room for considerable expansion in the breeding and feeding of pigs in this country is indicated by the large importation of ham and bacon.

As already indicated, the obvious reason why pig-feeding as carried on at the present time at the cheese-factories, does not provide a solution of the whey problem, is due to the small numbers of pigs employed. At many of the factories, during the height of the cheese-making season, from 600 to 800 pigs or more would be necessary to consume the whey;

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whereas, with several exceptions, the maximum accommodation of the piggeries is for about 300 pigs. The cost of erection of piggeries has now fallen from between £10 to £12 a pig in 1920 to below £4. There has also been a considerable fall in the price of pigs.

With the object of relieving the congestion due to the large production of whey at certain periods and at the same time easing the question of pig accommodation, the suggestion is made that

1. Farmers supplying milk to the factories take back on the return journey a share of the whey.

2. The partial or complete drying of part of the whey.

The former plan is carried out with a certain degree of success in other countries. Against the proposal there is the cost and trouble of carting and it would probably mean the erection of additional pig accommodation on some of the farms.

The latter has in it the germ of a complete solution of the problem. The obvious advantages are that dried whey, properly stored, keeps well; it possesses great nutritive value and it is in small bulk. Partial drying up to a concentration of about 70 per cent. is less costly. The syrup produced does not keep well but it can be fed directly to pigs or used for the extraction of milk sugar. There are two methods in use for drying, namely, the "roller" process and the "spray" process, each of which the writer has seen in operation. The following is a brief description of each.

The essential equipment of the roller¹ process consists of two horizontal steam heated revolving cylinders or rollers; each about 60 inches long with a diameter of 28 inches. The rollers are installed sufficiently close to each other to be in contact at the periphery. The liquid distributing tank with adjustable discharge is in the middle over and between the rollers. There are scrapers to remove the dried film and receptacles to catch the powder. The steam pressure inside the roller is sufficient to give a temperature of 124° C. A 4 H.P. engine would turn the rollers. Some of the cheese factories have an oil or gas engine and all possess boilers capable of giving a pressure up to 80 lbs. per sq. inch. There are at least seven types of roller plant².

The spray process, in the main, consists of desiccating the liquid by atomizing it in an atmosphere of heated air. The small particles of milk spray give up their moisture quickly and drop to the bottom of a drying

¹ James Milne and Son, Ltd., Manufacturers of Drying Machines, Edinburgh.

² Just process, U.S.A. Pat. 712,545, Nov. 1902, also Just-Hatmaker process; Gathman process, U.S.A. Pat. 834,516, Oct. 1906; Paasberg process, U.S.A. Pat. 726,742, April 1903; Ekinburg process, U.S.A. Pat. 785,600, March 1905; Gowes process, U.S.A. Pat. 939,495, Nov. 1909; Buflovak process, U.S.A. Pat. 1916.

chamber in the form of a fine powder, while the moisture-laden air escapes. The temperature of the chamber varies, according to circumstances, from 140° F. to 180° F. The process claims not to kill the enzymes nor to destroy the physical condition of the protein. There are many modifications, seven of which the writer has details of¹. But, as the process is more elaborate and costly than the roller one, it is not for this reason considered necessary to make any further comment.

One pair of rollers will dry up to 1000 gallons of whey daily. But by first concentrating the whey, the drying capacity of the rollers can be greatly increased. Concentration could be carried out in a vacuum² pan or in a single effect evaporator³. The latter would dry from 100 to 130 gallons of whey per hour up to a concentration of between 60 and 80 per cent. by weight.

Cost of drying is determined on the following basis:

Overhead charges.

Coal.

Labour.

Interest on capital, depreciation, etc.

Grinding or kibbling and packing of product.

Coal is the principal item in the cost of production. 1 lb. of steam evaporates 1 lb. water. 1 lb. coal, according to its calorific power and to the efficiency of the evaporating plant, will evaporate from 5 to 8 lbs. of water. Proportion of water in whey 93 per cent. and in dried whey 2 per cent.

Capital outlay exclusive of building.

A pair of rollers and accessory parts.

A single effect evaporator plant or vacuum pan.

An oil engine 4 to 8 H.P.

A boiler to give 80 lbs. pr. per sq. inch.

A roller drying plant, it is stated, would cost between £400 and £500 and a partial drying plant from £700 to £800.

Without access to factory records, and with wages and cost of material fluctuating, it is not possible to arrive at a true costings estimate. But from information supplied the cost of drying whey by the

¹ Rogers, U.S. Pat. 1,297,496, March 1919; Percy, U.S. Pat. 125,406, April 1922; Stauf, U.S. Pat. 666,711, Jan. 1901; McLachlan, U.S. Pat. 806,747, Dec. 1905; Morrell-Soule, U.S. Pat. 860,927, July 1907; Gray, U.S. Pat. 1,266,013, May 1918.

² Mirreles, Watson and Co., Ltd., Glasgow.

³ Kestner Evaporator and Engineering Co., Ltd., Westminster, London.

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roller process at the present time, May 1922, is round about 2d. per lb. or £18. 13s. 4d. per ton of dried whey.

Average composition of whey solid is shown below, Table XXII.

Table XXII.

Average composition of whey solids. Percentages.

		Dairy School	Factory A	Factory B	Average
Protein (total)	...	12.55	12.81	12.86	12.74
Fat	...	3.76	4.04	2.87	3.39
Milk sugar	...	69.18	68.69	71.22	69.70
Ash	...	7.19	6.54	7.64	7.12
Undetermined	...	7.32	7.92	5.91	7.05

Other outlets for whey solids are

Baking and confectionery trades.

Invalid foods, dietetic preparations, etc.

Extraction of milk sugar.

Poultry, calf foods, etc.

In bread-making¹ the whey solids add to the nutritive value of the flour and at the same time act as yeast food. In the confectionery trade the solids are used as constituents of baking powder². The lactic acid of the whey replaces all or part of the usual acid in baking powder. Use is also made of the solids as constituents of invalid foods³.

It is difficult to obtain reliable data to show the extent to which whey solids are employed for the purposes mentioned. In all probability the amount is relatively small.

Milk sugar.

Until recent years milk sugar was not manufactured in this country. Now there are at least three lactose factories in the United Kingdom, namely: The Government factory at Haslington; The Wholesale Co-operative Society's factory, Basford Bridge, both near Crewe; and the Lactose factory, Tipperary. The first two have been erected since the war, whilst the last has been in existence some years. When fully working the production of each factory is estimated at from 100 to 150 tons of milk sugar per annum.

*Importations*⁴ are given on p. 229.

¹ Improvement in the manufacture of bread, Tooth, Eng. Pat. 6103, 1891.

² Stillrell, U.S. Pat. 26,168, 1909.

³ Food Manufacture of Articles of, with the use of sour whey solids, Townsend, Eng. Pat. 158,684, 1919.

⁴ The figures were kindly supplied by the Statistical Officer, Customs and Excise, London, April 2, 1921.

	1920 lbs.	% of total	1913 % of total
Netherlands ...	303,752	33·7	40·2
United States ...	542,178	60·0	—
Victoria ...	5,600	0·6	—
Germany ...	49,280	5·5	44·2
Belgium ...	—	—	2·4
France ...	1,648	0·2	10·8
Italy ...	—	—	2·4
Total ...	902,458	—	—
Money value ...	£69,836	—	—
Price per lb. ...	18·4d.	—	—

Uses of milk sugar, information concerning which has been obtained mainly by correspondence, are summarised as follows:

Manufacture of infant and invalid foods.

Addition to diluted milk for infant feeding.

Pharmacy, homeopathic medicines, etc.

Manufacture of Chocolates.

„ Milk stout.

„ Lactic acid.

To consider these in turn:

Infant and invalid foods absorb the bulk of the milk sugar consumed in this country. Refined or B.P. lactose is mostly employed, though crude lactose containing some albumen and ash is also used in the preparation of nutritive foods. The amount present in proprietary foods varies¹. The quantity consumed by the larger firms manufacturing these foods will probably range from 20 to 60 tons per annum. The total consumption for the country may reach between 300 and 400 tons per annum.

Pharmacy. Pure or technical lactose is practically restricted in its use to medicines and dietetics. In pharmacy it is largely employed as a diluent and for the sub-division of drugs as in the administration of grey powder, calomel, etc. Further, in connection with homeopathic medicines it is useful as an absorbent of hygroscopic substances such as plant extracts, etc. The quantity used in this way is small.

Chocolate. Information obtained from a number of manufacturers goes to show that milk sugar is not at present a regular constituent of chocolate. The main reason for this is the fact that it has to compete with cane sugar. Being more costly and not as sweet, it could only partially replace the latter. Provided milk sugar could be manufactured at a lower cost, there appears to be considerable scope for its use in the chocolate industry.

Milk stout contains lactose. Being unfermentable by ordinary brewers

¹ See R. Hutchinson, *Food and Principles of Dietetics*, 1918.

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yeast, this sugar remains unchanged in the fermented product to which it communicates a particular flavour which is not easily obtained in any other way. Crude lactose is employed and its use for this purpose is controlled by patents¹. At present the amount used is probably about 150 tons per annum.

Lactic acid. The manufacture of this substance forms an insignificant outlet. The acid is only used in quantity by tanners, woollen dyers and calico printers. Starch² from maize, potatoes, etc. provides an alternate method for its preparation, so that the price of crude lactose must be such that it can compete with that of fermentable carbohydrates derived from the above sources.

Process of extraction.

The manufacture of milk sugar was originally started in Switzerland, but it has now extended to other European countries, to the United States and to the Colonies. The Swiss and German methods of manufacture represent the two different processes in use at the present time, a brief description of each is given below.

Swiss method consists in concentrating the whey to about one-third of its original volume by boiling in cheese kettles; the albumen which separates out is skimmed off along with the fat. The liquid is further concentrated to a suitable consistency and the product run into large enamel pans with rotatory stirrers where crystallization takes place. The residue is yellowish brown or chocolate in colour and consists of impure sugar called "sugar sand." It is consumed to a small extent as food but its principal outlet is for purification by sugar refiners. The above process is simple but wasteful as during the boiling part of the sugar is converted into a non-crystalline form and at 70° C. slight decomposition commences, the rate of which increases as the temperature rises³.

In Scandinavia whey is boiled down, in the same way as maple juice, until on cooling it solidifies into a yellow crumbly mass which is used as food (Primost). On adding buttermilk or whole milk to the whey before boiling, the product is pasty (Mysost)⁴.

*German method*⁵. Whey is neutralised with milk of lime and condensed

¹ Milk stout Eng. Patents 13528, June 1908, 1269, Jan. 1909.

² Claffin, A. A., "Manufacture and application of lactic acid," *Journ. Soc. Chem. Ind.* p. 516, 1897.

³ Fleischman, W., "The Book of the Dairy," p. 258, 1896, *Thorpe's Dictionary of Applied Chemistry*.

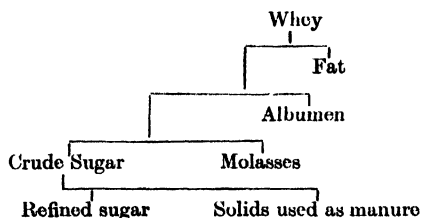
⁴ Decker, *Cheese-making*, p. 221, 1918.

⁵ T. Aufseberg, *Chem. Zeit.* **34**, p. 885, 1910; J. Pedersen, *Journ. N. Zealand Dept. Ag. Chem. and Drug.* March 1913.

to about 60 per cent. in a vacuum pan until the specific gravity reaches 30° to 32° B. The thick syrup is then run into shallow vats and occasionally stirred during the first ten hours. To separate the crystals the sticky mass is mixed with cold water and centrifuged and the lactose crystals obtained are washed on a drum. Two-thirds of the milk sugar is extracted in this way, the remainder being left in the syrup. The latter is heated to boiling, the coagulated albumen skimmed off and the liquid again concentrated *in vacuo* to 35° B. After cooling the lactose separates, it is washed and the quantity recovered amounts to a percentage of 0.3 to 0.7 of the whey. About 4 per cent. raw milk sugar is obtained from whey. The raw milk sugar is refined, for details of method the original papers referred to must be consulted. The refined sugar is equal to from 2.5 to 2.6 per cent. of the whey. Various modifications of this process are in use¹.

In connection with the evaporation of milk and whey and the extraction of sugar, there are a number of important physico-chemical problems awaiting solution. Among them may be mentioned—the escape of gas accompanied by great frothing from colloidal solution; the crystallization of milk sugar in presence of soluble salts and substances which react upon the sugar; the separation of colloidal substances like albumen in a condition for use as human food or dried into a condition for storage either for consumption as cattle food or for industrial purposes.

By-products are formed at different stages in the process of extraction, and a graph to represent these is shown below.



Cost of production.

As already remarked in the case of whey powder it is inadvisable, without access to records of factory working, to attempt to give actual costing figures. But it may be mentioned that in pre-war days, machinery, exclusive of the building, to handle 4000 gallons of whey daily is stated

¹ Mumford, U.S. Pat. 1,366,822, 1921; Dietrick, U.S. Pat. 1,201,027, 1916; Martin, Eng. Pat. 161,887, 1921, etc.

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to have cost about £2000, and between the years 1900 and 1910 the cost of production of lactose from whey, valued at $\frac{1}{2}d.$ per gallon, varied from £40 to £62 per ton¹. This does not take into account the value of the by-products, of which albumen is the principal. By the Swiss method of extraction, £20 per ton for crude lactose has been put as the cost of extraction.

Dempster² states that it requires six men and six tons of coal to produce one ton of sugar and that the cost of extraction is $6d.$ per lb. On the other hand the cost of coal per lb. of sugar is put at from $3d.$ to $4d.$ to which is added another $5d.$ to cover labour and necessary expenses, making a total of from $8d.$ to $10d.$ per lb.³ of sugar.

At the present time (May 1922), in this country, a complete sugar extraction installation to deal with from 3000 to 5000 gallons of whey daily, exclusive of the building, would cost between £9000 and £10,000, the minimum cost of production being put at $1s.$ per lb. of sugar.

A regular supply of whey amounting on an average to not less than 1000 gallons daily over a period of from 8 to 9 months would be necessary, otherwise overhead charges would become excessive and would considerably augment the cost of production. In absence of fresh whey, whey solids could be used as the raw material and the refining of the crude lactose would form part of the routine factory work when the cheese-making season is past.

Against the cost of production of milk sugar must be placed the value of the by-products a short description of which is given below.

Whey cream and butter. At the factories in Switzerland, Austria, Holland, Bavaria, etc., the practice is to skim the whey, formerly by hand, later by a milk separator and more recently by a whey separator and to churn the cream into butter. Since 1912 most of the American cheese factories have installed whey separators and have found them profitable. The whey should be separated as quickly as possible after it is drawn from the vat. From there it should run by gravitation into the whey tank. As the whey passes from the tank to the centrifugal machine, the small pieces of curd invariably present should be first strained out. The separator should be adjusted so as to produce cream containing from 50 to 75 per cent. of fat. The cream, which is sometimes pasteurised, can be used for making butter or for use in ice-cream, etc. When separated by skimming after the whey has been standing in a tank, the

¹ Pedersen, *loc. cit.*

² Dempster, N., "Milk Products in Europe and America," *Bull.* 86, *New Zealand Dept. of Ag.* p. 13, 1920.

³ From *International Sugar Journal*.

cream (owing to certain decomposition changes) is regarded as a half worthless product¹.

The yield will depend upon the percentage of fat in the whey. The average percentage of fat in whey from Cheddar cheese in these experiments was 0.23. One thousand gallons of whey would yield 27 lbs. of whey butter. Whey butter is softer and is reputed not to keep as well as milk butter. The price of this butter manufactured in this country is put at from 9d. to 10d. per lb.²

The question of making whey butter is largely a matter of cost of production. According to Van Slyke it would not be profitable to remove the fat unless the daily supply was 1000 gallons of whey containing 0.25 per cent. fat³. The initial cost is the installation of a separator. A centrifugal separator to deal with 500 gallons of whey per hour would cost under £200⁴. Guthrie gives a detailed cost of production⁵. In the United States "whey butter" must be sold and labelled as such⁶.

By skimming off the fat the nutritive value of the whey for pig feeding is diminished. For this reason it is necessary to decide whether it is more profitable to sell fat as whey cream or feed it to pigs. Relative market values will determine this point.

Whey albumen is a particularly valuable substance and its separation, in a form so that it could be marketed either alone or in an admixture, is a matter which, as yet, is hardly beyond the experimental stage. In Austria, Switzerland, France, etc., the albumen which separates on heating whey is made into Ziger⁷, Ricotta or Ricorta⁸ cheese.

Molasses and manure are other by-products.

Until the forementioned products become established articles of trade in this country their commercial value remains uncertain. Nevertheless, they form an essential part of any scheme for utilising whey.

Miscellaneous uses of whey.

Owing to the space which it would occupy, it is not considered necessary to give details of the minor uses to which whey is put. But the following list with references is given:

¹ *Milk, Cheese and Butter*, Oliver, London, p. 81, 1891.

² Supplement No. 16, *Journ. Bd. of Ag.*, Sept. 1916, p. 24.

³ Van Slyke and Publow, *Science and Practice of Cheese-making*, p. 65, 1914.

⁴ Watson Laidlaw and Co., Ltd., Dundas Street, Glasgow.

⁵ Guthrie, *The Book of Butter*, Chap. XIII.

⁶ Hunziker, *The Butter Industry*, p. 581, 1920.

⁷ Fleischman, *Book of Dairy*, p. 268, 1896.

⁸ Decker-Sammis, *Cheese-making*, p. 219, 1918.

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Vinegar from whey¹; manufacture of alcohol²; an antimony mordant from whey³; whey lemonade⁴; malted whey⁵ use in the manufacture of bread, cakes, biscuits, etc.

SUMMARY OF RESULTS AND RECOMMENDATIONS.

1. The yield of whey from the manufacture of cheese in Scotland in 1920 amounted to between 17,000,000 and 18,000,000 gallons, which is equivalent to over 10 per cent. of the milk production of the country. About one-half was produced at the farms and the remainder at milk factories.

The average daily production on a farm was about 112 gallons with a minimum of 12 and a maximum of over 300. The corresponding figures for the season being 26,000 with a minimum of 600 and a maximum of 84,000. The cheese-making season lasts on an average 227 days, the shortest period being 60 and the longest over 300 days.

Of the milk factories which number approximately 50 one-half are owned by Co-operative Dairy Farmers Associations and most of them are affiliated with the Scottish Agricultural Organisation Society. The milk handled by these centres amounted to almost 20 per cent. of the total production for Scotland. Nearly 75 per cent. of the factories make cheese. The average consumption of milk for cheese-making is about 41 per cent. of the annual turnover, the minimum being 2 per cent. and the maximum 90 per cent. The average daily yield of whey per factory varied from 100 gallons to over 3000. For the season the average yield was 233,000 with a minimum of 8000 and a maximum of 554,000. The factory cheese-making season lasts on an average 165 days with a minimum of 130 and a maximum of 214.

2. On the farm provision is generally made on a sufficient scale for the consumption of the whey by pig feeding. Owing, of late years, to a scarcity of home-bred and imported pigs, there have been unavoidable losses.

At the factory several thousands of gallons require to be disposed of daily. A few factories continue to run the whole of it to waste, but most of them have attempted to deal with it as pig food. However, in

¹ Process of obtaining table liquor, Lamsuroux p. Paris, Eng. Pat. 5562, 1909; Kokosingki, M. Mond, *Prod. Chem.* **12**, p. 194.

² Von Bohle, "Whey and skim milk for diluting molasses, use of," *Cent. Zuckerind.* **15**, 68. 70.

³ Kritschmar, M., *Chem. Zeit.* **12**, p. 943.

⁴ Burri, R., "Die Molkenlemonade," *Molkerei-Zeitung*, **5**, p. 81, 1913.

⁵ Stillwell, J. S., U.S. Pat. 1,041,896, 1912.

many cases, the pig accommodation provided is not sufficient to allow for a consumption, during certain months of the year, of much more than one-half of the daily production. The remainder is either discharged into streams, or at considerable expense, sprayed on the land as manure.

3. Unexpected differences were found in the composition of factory milk used for cheese-making. The cause of this was due to the use of mixed evening and morning milk compared with morning milk only. The solids in the former gradually increased with advance of the season, whilst in the latter they remained stationary. The average proportion of casein in milk was 3.06 per cent. and of albumen and other forms of nitrogen 0.51 per cent. The ash was found to be subject to variation according to season and stage of lactation.

4. Whey is a by-product of milk and its chemical content is primarily determined by that of milk, but the principal cause of variation is due to different or defective methods of cheese-making. In the course of this investigation it was shown that the fat content was independent of that in milk. In respect to milk sugar bacterial activity was the deciding factor. Whey, stored in bulk for 80 days and tested weekly, showed a decrease of milk sugar from 4.9 to 2.8 per cent. The albumen, except under defective methods of cheese-making, is determined by that in milk. But the amount of caseose nitrogen varies with the extent of enzyme action. As an example of the last, reference is made to the change in the nitrogen content of whey produced at different stages in the process of cheese-making when the action of rennet enzymes play a decisive part. Acidity being essentially a bacterial product of milk sugar, up to a certain point varies inversely with the latter. Increased concentration of acid in milk brings into solution a portion of the insoluble mineral constituents.

There was a slight increase in the solids in whey corresponding with those in milk, as the season advanced.

Variation in the ash was considerable, a result which is probably a little magnified owing to a difficulty in determining the ash, by the direct ignition method, adopted in the early part of the investigation. The lime and the phosphoric both increased in the whey as the cheese-making season advanced. The mineral constituents are present mostly in combination with lactic, phosphoric and hydrochloric acids.

5. The average proportion of milk constituents passing into the whey were determined.

6. In respect to the general properties of whey. On standing, a thin layer of fat separates almost at once and a slight sediment of curd de-

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posits. Within 24 hours the sugar content falls and the acidity rises, each by nearly $\frac{1}{2}$ per cent. The acid precipitates the albumen and the liquid soon becomes lumpy and a scum forms. Moulds and other organisms make their appearance and for the next 14 days or so, as judged by the sugar content, little further change appears to occur. After that it is evident that a series of fermentation changes were in progress. There was a constant evolution of carbon dioxide and the percentage of sugar falls at the rate of 0.2 to 0.3 per cent. per week. After 80 days a drop in the percentage of sugar from 4.9 to 2.8 per cent. was registered. In the same period the acidity expressed in terms of lactic acid, increased from 0.14 to 0.64 per cent. The average temperature was 54° F.

7. As to the nutritive value of whey 50 lbs. (5 gallons approximately) of whey on an average produce 1 lb. live weight increase (pigs) which is equal to 0.75 lb. dressed carcase. For dressed carcase the current market price is 126s. per cwt., equal to 1s. 1d. per lb. (May 1922). Therefore on the above basis the return in dead meat fixes the value of whey consumed at 2d. per gallon.

Calculated on the whey solids the value works out as follows: whey contains 6.86 per cent. of solids, 50 lbs. whey will therefore contain 3.4 lbs. solid, its equivalent in dressed meat is 0.75 lbs. Therefore dressed meat at 1s. 1d. per lb. fixes the value of whey solids consumed at from 2d. to 3d. per lb.

As to the presence of accessory food substances, there is direct evidence to show that whey possesses a food value over and above that supplied by the protein, fat and carbohydrate which it contains. This is a fact of considerable practical importance and further elucidation of this property by feeding trials with pigs is needed. It is stated that whey is lacking in vitamin A, a deficiency which can easily be made good from other sources.

Fed in moderate quantities and supplemented with suitable meals, whey has proved itself an excellent food both for growing and for fattening pigs. Moreover it is the opinion of bacon curers that whey improves the quality of bacon.

Attention however must be directed to the fact that the nutritive value of whey diminishes with storage. It should be utilised on the day of its production. The whey tank should be emptied daily and occasionally thoroughly cleaned.

8. Manure value per ton of whey based upon the amounts of nitrogen phosphoric acid and potash works out one half-crown.

Used in pot experiments with oats in quantity to supply nitrogen

equal to that contained in a dressing of 1 cwt. of nitrate of soda per acre, a yield considerably above that from the control pots was obtained. The yield was further increased by neutralising the whey with lime.

9. Considering the question of utilisation, the conclusion arrived at as a result of this investigation is that pig feeding must provide the main outlet for whey. In coming to this decision account was taken of the following facts:—(1) A considerable amount of capital has already been expended in the erection of piggeries at factories, the cost of which has now fallen from a war-time estimate of between £10 to £12 a pig to below £4 a pig. (2) Importations of ham and bacon into the United Kingdom in 1919 amounted to a value of £90,000,000. (3) Whey is a cheap and excellent pig food. The return in meat for whey consumed is equal to a value at present (May 1922) dressed carcase prices of 2*d.* per gallon exclusive of manure value. Eight million gallons is the estimated annual production of factory whey in Scotland which at 2*d.* per gallon works out at a value of over £66,600. (4) In the past factory authorities have been somewhat indifferent to the potential value of whey. Realising its true value there may now be less reluctance in making adequate provision for its utilisation. Apart from the conversion of whey into valuable human food the nuisance which it creates by discharging it into streams would be avoided. Pig manure can be readily disposed of and is a source of revenue.

With the object of minimising, or of preventing the congestion due to the large amount of whey produced during certain months, the suggestion is made that part of the whey be dried and used as pig food or for other purposes. Complete drying over steam heated rollers at current values of coal and overhead charges is round about 2*d.* per lb. of dried whey. No special technical training is required to work the drying plant. Partial drying up to a concentration of 70 per cent. would cost less. 3·4 lbs. whey solids produce 1 lb. live weight increase, which, as already explained, works out at a value of between 2*d.* and 3*d.* per lb. of dried whey.

But just as it is uneconomic to equip milk factories where cheese production is on a small scale and for short periods with a complete cheese-making plant, so it would be unsound economically to install a drying plant at all factories. The suggestion is made that in Ayrshire, for example, where there are eight factories, each affiliated with the Scottish Agricultural Organisation Society, and within a radius of ten miles, there would be co-operation in the sense that cheese-making should be restricted to certain factories only. Co-operation on these lines would inevitably tend to lower the cost of production.

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Dried whey is a valuable food for poultry, calves, in fact, all stock. Other outlets for it are in bread-making, nutritive foods, for the extraction of milk sugar, etc.

10. The alternative to pig feeding is the extraction of milk sugar and other substances. In approaching this matter there are several leading facts to be considered. (1) The annual consumption of milk sugar in Great Britain is probably between 500 and 700 tons, most of which at present comes from abroad. Before the war there is ample evidence of over-production and that the substance was a "drug" on the market. There are over 350 milk factories in Great Britain. (2) The cost of extraction of milk sugar at the present time is estimated at 1s. per lb. The outlets at its present market price are restricted. Its principal competitor is cane sugar which is sweeter and is sold at a lower price. (3) Countries where the extraction of milk sugar is an old established industry have the initial advantage of existing factories equipped for this purpose. Further, a sugar extraction plant is often associated with a milk products factory which provides an outlet for sugar in the form of proprietary foods. (4) The yield of milk sugar is estimated to be equivalent to a 2.5 per cent. in whey. The value of the by-products are not sufficient to lower the high cost of sugar extraction.

Comparing further the two outlets for whey (1) as pig food and (2) for the extraction of sugar. In the former capital outlay is confined mainly to the erection of piggeries, and probably a drying plant; the latter involves the erection of a special building, installation of an expensive plant, and a technically trained staff.

RECOMMENDATIONS.

1. That pig feeding at milk factories be extended so as to deal effectively with all the whey produced.

2. That cheese-making be restricted to factories where reasonable quantities of cheese are made and the season is of reasonable length and that arrangements with this end in view be made between affiliated co-operative associations of dairy farmers.

3. Where necessary a plant for drying whey be installed.

4. The erection of a drying plant at a suitable centre for the purpose of providing material for research connected with the value of whey, of dried whey and of dried separated milk for pig feeding and other uses.

5. The establishment of a factory in Scotland for the manufacture of milk products other than cheese and butter.

In conclusion the writer wishes to express his thanks to the managers of milk factories; to Professor Drummond, the Dairy School, Kilmarnock; to Mr John H. Wyllie, The United Creameries, Ltd., Stranraer; to Mr John Drysdale, Scottish Agricultural Organisation Society, Edinburgh; to Mr. J. Scott-Herriot, Mirrlees Watson and Co., Ltd., Glasgow; to Mr J. Arthur Reavell, The Kestner Evaporator and Engineering Co., Ltd., London; to the Manager of the Government Lactose Factory, Haslington, Crewe; to the Manager, Messrs Truefood, Ltd., for providing facilities and supplying data, also to Mr Peter Caldwell for invaluable help in the analytical work connected with this investigation.

Additional expenditure incurred in carrying on this investigation was defrayed by the Board of Agriculture for Scotland.

NOTE. This paper forming part of a Thesis, forwarded on June 7th. 1922, was accepted by the University of Glasgow for the degree of Ph.D.

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THE NATURE OF THE PIGMENT OF SILAGE.

By HERBERT ERNEST WOODMAN, PH.D., D.Sc.

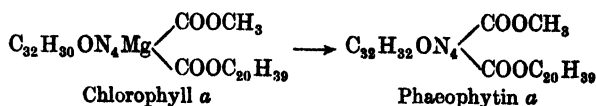
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IN investigations dealing with the changes undergone by constituents of green crops during the process of ensilage, no attention has hitherto been paid, so far as the writer is aware, to an interesting transformation which affects the chlorophyll ingredient. That the green pigment does not remain unchanged during the process is apparent from the colour of the material as taken from the silo. The fresh green appearance of the newly cut crop is found to have changed to a colour varying, according to the conditions of ensiling, from a dark olive green shade to a dark brown.

This fact, in conjunction with the appearance of ethereal extracts of silage, led the writer to direct his attention to the chemical nature of the silage pigment.

The chemistry of chlorophyll and its derivatives has been placed on a firm basis during the last twenty years by the researches of Willstätter and his co-workers(1). It is now established that magnesium is an essential constituent of the chlorophyll molecule, and that the latter displays extreme instability in the presence of acids. The action even of weak acids like oxalic acid on chlorophyll results in the quantitative splitting off of the magnesium, with the formation of a magnesium-free derivative known as phaeophytin. The latter is simply chlorophyll in which the magnesium has been quantitatively replaced by hydrogen.

If, for instance, a concentrated alcoholic solution of oxalic acid be added in the cold to an alcoholic solution of chlorophyll, the colour changes rapidly to a dark olive brown and a black precipitate of phaeophytin begins to separate out. The change may be represented as follows:



A similar transformation occurs with chlorophyll *b*.

Jørgensen and Kidd(2) have shown that the same change can be brought about by the action of carbon dioxide. If a colloidal solution

of chlorophyll be exposed to an atmosphere of carbon dioxide in a sealed tube, the pigment rapidly turns yellow or brown owing to its conversion into phaeophytin.

A consideration of the foregoing leads naturally to the assumption that some such change occurs in the silo and is responsible for the change in colour which the green crop undergoes. It would be anticipated that the chlorophyll of the green plant would undergo conversion into phaeophytin as a result of the action of the carbon dioxide and organic acids developed during fermentation. An investigation of ethereal extracts of silage proved this supposition to be correct.

500 gm. of green "fruity" oat and tare silage was extracted with ether. The filtered extract was of a brown green shade, showing, however, when viewed in bulk, a vivid dark red colour. Evaporation of the solvent left a black waxy residue, which was only slightly soluble in cold alcohol, more soluble in hot alcohol and almost insoluble in petrol ether. The alcohol and acetic acid solutions showed the same shades of colour as noted in the ethereal extract. These preliminary observations pointed to the presence of phaeophytin in the ether extract of the silage.

In order to make a closer study of the colouring matter of the silage, a quantity of the pure pigment was isolated in the following manner. The ethereal extract of silage was evaporated on the water bath and the residue was taken up in warm alcohol. The alcoholic solution was next poured into a large volume of distilled water, this yielding a colloidal solution of the pigment possessing a yellowish brown colour. The pigment itself separated as a brownish black flocculent precipitate on stirring a little salt into the solution. It was filtered off, well washed with water and was found to exhibit the characteristic properties of phaeophytin.

(1) It was only slightly soluble in cold alcohol, but much more soluble in the hot solvent. On cooling the hot solution, the bulk of the pigment came out again. The colour of the solution in thin layers was olive brown; in bulk, however, it was dark red.

(2) The pigment was fairly soluble in acetic acid, easily soluble in chloroform, but almost insoluble in petrol ether. The colour of the solutions resembled that of the alcoholic solution.

(3) When the alcoholic solution was shaken with a trace of copper acetate, the olive brown colour gradually disappeared and ultimately the solution took on an intense green shade, without fluorescence.

(4) On shaking the alcoholic or acetic acid solution with a little zinc acetate, a beautiful blue green solution was obtained which showed a strong red fluorescence.

(5) The addition of ferric chloride to the alcoholic solution caused the immediate production of a green coloration.

(6) Addition of a drop of concentrated nitric acid to the solution of the pigment in glacial acetic acid gave a strong blue colour, which gradually faded to reddish brown and ultimately to yellow brown.

The results of the above tests establish the identity of the silage pigment as phaeophytin. In fact, silage would make an excellent starting point for the preparation of phaeophytin on a large scale.

In view of the fact that the colour of silage may vary between olive green and dark brown, according to the conditions obtaining during ensilage, it was next of interest to ascertain whether brown silage contained the same pigment as the so-called green "fruity" silage. Accordingly a dark brown, almost black, sample of oat and tare silage was extracted with ether and the pigment isolated in the manner described above. It was found to be phaeophytin. It may thus be concluded that all types of silage, no matter what their colour, contain the pigment phaeophytin. The pigment itself in the free state may be obtained in forms varying in colour from olive green to yellowish brown and brownish black. In all probability the colour depends merely on the state of molecular aggregation of the colloidal pigment. The colour of silage is therefore not to be regarded as a safe guide in regard to quality.

The change of chlorophyll into phaeophytin during ensilage does not, of course, possess any significance from the nutritional point of view.

A sample of maize silage was next investigated in a similar manner and was found to owe its colour to the presence of phaeophytin.

Since phaeophytin possesses the character of an ester, its presence in the alcoholic silage extracts as prepared for titration might be expected to interfere with the estimation of the amino acids(3). To test this point, 500 c.c. of such an alcoholic extract were evaporated to a small bulk *in vacuo* at 45° C. The concentrated solution was found to contain only a trace of the pigment, the amount being too small to affect the accuracy of the method for estimating the amino acids in the silage extracts.

SUMMARY.

It has been shown that the pigment in silage is phaeophytin, the magnesium-free derivative of chlorophyll. It is produced from chlorophyll by the action of carbonic acid and organic acids developed during fermentation in the silo.

REFERENCES.

- (1) WILLSTÄTTER and STOLL, *Untersuchungen über Chlorophyll. Methoden und Ergebnisse*. Berlin, 1913.
- (2) JØRGENSEN and KIDD, *Proc. R. Soc.*, B, 89, 342, 1917.
- (3) AMOS and WOODMAN, *J. Agric. Sci.*, 12, 345, 1922.

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THE PHYSICAL SIGNIFICANCE OF THE SHRINKAGE COEFFICIENT OF CLAYS AND SOILS.

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SECTION I. INTRODUCTION.

THE shrinkage coefficient of a soil may be defined as the maximum percentage decrease in length (linear coefficient) or in volume (cubical coefficient⁽¹⁾) which is exhibited by a block of the soil that has previously been worked up with water to a standard degree of plasticity, and then allowed to dry in air.

Investigations into the significance of the shrinkage coefficient were initiated in the West Indies by Watts in 1908. One of the aims of these investigations was to examine the relationship between the shrinkage coefficient and the clay content of soils. It was thought that the two might be directly correlated, on the assumptions that (1) shrinkage is due to evaporation of the water-films that surround the component particles of a moist plastic soil, and (2) that the *degree* of shrinkage is decided by the relative initial thickness of the water-films, being therefore greatest in soils whose particles are of smallest average diameter⁽²⁾. These assumptions are based on the mineral-grain and water-film hypothesis of the nineteenth century soil physicists.

A simple method of measuring soil shrinkage coefficients was devised by Watts. The soil is kneaded by hand with water in amount sufficient to confer a "suitable degree of plasticity" on it. It is then pressed into an open-ended wooden mould of dimensions $3 \times 1 \times 1$ inches. The material that overflows is cut away, and the block of soil removed. Two fine pins are inserted almost to their heads into the block, at a distance apart of approximately 50 mm. The exact distance is subsequently measured with a scale. The block is then allowed to dry in air, and its maximum percentage linear shrinkage determined after the lapse of a suitable period of time.

The method would appear to be somewhat crude. Distortion introduces serious error. This can be minimised, however, by placing the drying block on a piece of paper or wire net, and by frequent turning.

Another source of error, which, at first sight, might seem to be much more serious, is the difficulty of gauging a "suitable degree of plasticity" to which the soil should be brought prior to shrinkage measurements being made. In testing this point, Lake noted that comparatively small variations in moisture content resulted in relatively large variations in plasticity. When water is added in successive amounts, a quite definite stage is reached when the kneaded soil can be moulded with greatest facility. This stage has been termed the "point of maximum plasticity (3)," and has been accepted by West Indian workers as the standard of plasticity in shrinkage experiments. It can be readily judged by feel; there would appear to be no practical advantage in identifying it by crushing tests (3a). When the precautions and conditions indicated are observed, replicate trials yield values for the coefficient of shrinkage that possess low probable errors.

Auchinleck compiled data which he accepted as indicating an approximate proportionality between the percentage of "colloidal clay" (estimated by conventional sedimentation and precipitation methods) and the linear shrinkage coefficient. His figures for moisture contents at the point of maximum plasticity, however, apparently show no very marked relationship to shrinkage coefficients. If the shrinkage coefficient and the moisture content of a soil at the point of maximum plasticity both depend on the percentage of clay present, as was originally postulated, the proportionality, as Auchinleck points out, should in each case be very exact.

It became evident that further research was necessary in order to test the accuracy of the preliminary experiments. Accordingly, Tempany conducted an extensive investigation, the final results of which were presented in a paper published in 1917 (4). He modified the originally accepted water-film hypothesis by introducing certain concepts of colloid science. He assumed, for instance, that soils at the point of maximum plasticity contain the whole of their water in union with colloidal material in the form of a gel. Shrinkage he explained as due to the contraction of the gel skeleton which was supposed to ramify throughout the plastic mass, and to enclose in its meshes the component soil particles. Tempany's experimental data prove that the magnitude of this contraction, at least during the early stages of shrinkage, *is numerically equal to the volume of water lost by evaporation*. A marked shrinkage lag occurs however as the soil block continues to dry. Tempany explained this lag by assuming that internal frictional forces begin to operate when the soil particles are drawn near to one another by the contracting gel skeleton. Beyond

this point, shrinkage soon ceases altogether; continued evaporation finally results in the rupture of the gel. The point at which the shrinkage lag sets in, and the magnitude of the total shrinkage observed, appear, according to Tempany, to be simple functions of the colloid content of the soil.

Further work on the relationship between the shrinkage coefficient and the pore space in contracted (oven-dried) soil-blocks caused Tempany definitely to conclude that the shrinkage coefficient and the colloid content of a soil are simply correlated. The correlation was tested experimentally by comparing the shrinkage coefficient with the percentage of colloidal clay separated from soils by conventional methods of mechanical analysis. The results were considered completely to confirm the conclusion. *

It is a matter of some surprise that Tempany neglected further to examine the possible relationship between the shrinkage coefficient and the moisture content of soils at the point of maximum plasticity, especially in view of the great suggestiveness of Auchinleck's statement, and his own premise that soils at the point of maximum plasticity contain all their water colloiddally imbibed in the soil hydrogel, for, if this be so, then the relative colloid contents of soils can be estimated by simply comparing their moisture contents at the point of maximum plasticity.

Mason (5) has recently extended Tempany's work by comparing the two constants for a series of Barbadian soils of different geological types. His results very strikingly indicate a great discrepancy between the ratios of the moisture content at the point of maximum plasticity and the linear shrinkage coefficient as determined for red upland soils and for black or grey calcareous lowland soils. The figures for this ratio are 5.48 and 5.55 for the red soils and 3.33 and 3.37 for the others. Mason came to the conclusion that the divergencies are due to marked aggregation of the soil particles in the case of the red soils. He assumed that the compound soil particles "are not destroyed, at least permanently, in kneading the soil preparatory to shrinkage determinations," and explained his results by applying Tempany's theory of shrinkage with the necessary modification demanded by this assumption. Mason did not extend his investigations to include both aggregated and non-aggregated soils of the same geological type, nor did he doubt the veracity of Tempany's theory. He noted, however, that a simple correlation apparently exists between soil moisture residues at permanent wilting and the percentage of moisture at the point of maximum plasticity.

SECTION 2. EXPERIMENTAL.

I. In order further to test the relationship between the linear shrinkage coefficient and the moisture content at the point of maximum plasticity for soils of the same geological type but exhibiting different degrees of aggregation, the writer has examined a series of Antiguan soils of varying calcium carbonate content, obtained at points in a half-mile traverse across an area of clay land bordering a limestone hill-range. The more calcareous of the top-soils possess a marked crumb structure; the sub-soils and the soils low in calcium carbonate, are, in general, devoid of crumb.

Table I. *Shrinkage coefficients of soils of similar geological type, but possessing different degrees of aggregation.*

	1 CaCO ₃ content*	2 Degree of dispersion†	3 Moisture con- tent at point of maximum plasticity‡ (P)	4 Linear shrinkage coefficients§ (a)	5 Ratio (P) (a)
Cultivated soils					
A 1 Top	23.8	9	43.6	11.6	3.76
Sub.	22.3	10	44.1	12.2	3.61
A 3 Top	10.0	7	45.4	13.6	3.34
Sub.	8.7	9	45.8	12.8	3.59
A 6 Top	2.4	6	45.6	12.1	3.85
Sub.	2.0	13	45.4	11.8	3.76
A 9 Top	1.2	22	45.2	11.7	3.87
Sub.	0.6	70	42.2	10.8	3.90
A 12 Top	0.2	36	47.2	12.2	3.87
Sub.	0.3	50	46.4	12.6	3.68
Uncultivated soils					
A 14 Top	24.3	35	46.6	12.9	3.61
Sub.	41.5	400	42.0	12.7	3.31
A 16 Top	8.3	18	48.1	13.8	3.46
Sub.	4.5	24	45.6	12.4	3.67
A 18 Top	1.3	18	39.7	11.4	3.48
Sub.	1.1	276	43.0	11.3	3.80
A 19 Top	0.2	50	39.1	10.9	3.59
Sub.	0.2	122	43.6	11.6	3.76
A 21 Top	0.1	62	45.8	12.5	3.66
Sub.	0.1	85	46.1	12.6	3.66

* Determined by Amos's method (*Journ. Agric. Sci.* 1905, 1, 322).

† Milligrams of suspended matter in 50 c.c. of liquid pipetted from the upper part of a 25 cm. column contained in a cylinder into which water and the silt and clay fraction from 50 grms. of the soil had been allowed to stand for 24 hours. At least two determinations were made on each soil sample.

‡ Determined by drying at 110° C., material that had been worked up to the "point of maximum plasticity," and then moulded into blocks. (The blocks were also used for shrinkage determinations.) The values are means of five replicates. The mean probable error of this number of replicates for P was found to be ± 0.26 .

§ Determined by Watt's method. The mean probable error of five replicates for a was found to be ± 0.18 .

The experimental results are presented in Table I. Here the degree of aggregation is expressed by its converse, the degree of dispersion. No attempt has been made to express crumbiness. The data indicate that the linear shrinkage coefficient in each case is closely correlated with the moisture content at the point of maximum plasticity, notwithstanding the great variations in degree of aggregation. This result is contradictory to Mason's views that kneading fails to disintegrate the soil floccules, and that aggregation influences shrinkage.

The figures also afford interesting comparisons between calcium carbonate content and degree of dispersion, which, however, will not be discussed in this place.

II. The results of the last experiment suggest that a different explanation is needed to elucidate the abnormality exhibited by Mason's red soils. The writer consequently determined certain moisture constants for a series of West Indian soils of different geological origin, and including soils of a red colour. The numerical values obtained are set out in Table II. The samples examined in this and in subsequent experiments belong to four main types.

Type 1. *Soils derived from volcanic rocks of hypersthene-andesitic origin.*

(a) Montserrat (6); sands, loams and clays, derived from breccia or ash.

(b) Antigua (7) (Bendals), Barbados (8) (Scotland District); sedentary soils overlying estuarine clays.

Type 2. *Soils overlying sedimentary calcareo-siliceous clays.*

Antigua, northern margin of central plain; "upper tuffs" (Oligocene) of Purves (9); "transition limestone soils" of Tempany.

Type 3. *Soils overlying sedimentary siliceous non-calcareous clays.*

Antigua, central plain; "volcanic sands and chert" (Oligocene) of Purves.

Type 4. *Red lateritic soils.*

(a) Dominica (10); clays derived by intense weathering from hypersthene-andesitic rocks of Pleistocene age.

(b) Barbuda, Barbados (8, 11, 12); residual clays overlying coral limestone of Pleistocene age, and derived probably from intercalated contemporaneous volcanic ash of hypersthene-andesitic relationship.

The data in Table II confirm Mason's observation that the ratio between moisture content at the point of maximum plasticity and the linear shrinkage coefficient (column 6) varies considerably in soils of different geological origin, being abnormally high in the case of the red soils examined (D 1, BaR and BsR). In spite of this fact, *each of the*

soils ceased finally to shrink when the moisture content of the plastic brick had been reduced to a point which approaches the hygroscopic coefficient stage (column 7). Evidently great significance attaches itself to the hygroscopic coefficient in soil shrinkage phenomena.

Table II. *Relationships between certain moisture-constants and shrinkage coefficients of soils of different geological types.*

1	2	3	4	5	6	7	8
Soil type	Linear shrinkage coefficient (a)	Moisture content at point of maximum plasticity (P)	Moisture residue at cessation of shrinkage* (R)	Hygroscopic coefficient† (H)	Ratio (P) (a)	Ratio (R) (H)	Ratio (P) (H)
	% on plastic brick	% on oven-dried soil					
Type 1 (b) Bdl	10.0	33.7	10.2	7.2	3.37	1.44	4.68
BsS	10.6	37.5	10.3	8.1	3.53	1.27	4.63
Type 2 A 24	12.1	40.9	12.1	10.2	3.38	1.17	4.01
Type 3 A 21	13.8	46.2	11.4	10.9	3.35	1.05	4.24
Type 4 (a) D 1	10.7	54.5	15.9	15.5	5.06	1.03	3.49
(b) BaR	13.9	57.2	18.1	16.6	4.12	1.09	3.44
BsR	8.6	48.8	21.8	20.6	5.77	1.06	2.37

* Estimated by half-daily weighings and measurements of drying blocks of soil.

† Determined by Hilgard's method as modified by Mitscherlich and by Beaumont (*Cornell Univ. Ag. Exp. Sta. Mem.* 1919, 21, 497). 10 % sulphuric acid was used in the humidifier. The recorded results are each the mean of five replicates carried out on air-dried soil that had been sifted through a 1 mm. sieve. They are lower than the more accurate values obtained by the use of pure water. (See Alway, Kline and McDole, *Journ. Agric. Res.* 1917, 11, 147.) The mean probable error of five replicates for *H* was found to be ± 0.23 .

If we concede that the moisture content at the point of maximum plasticity marks the saturation stage of the soil colloids (13), we can simply explain variations in the shrinkage coefficient of soils of different geological types by assuming that the total imbibed water of soil colloids exists in two phases. Removal by evaporation of water in the first phase causes shrinkage to occur. On the other hand, removal of water in the second phase is accompanied by no further decrease in volume. The two phases merge imperceptibly one into the other. The point which marks this transition corresponds approximately to the hygroscopic coefficient point. The ratio between the amounts of total imbibed water and water in the second phase (hygroscopic moisture) evidently varies in soils of different geological types (column 8, Table II). It is significantly lower in the red soils examined than in soils of the other types. The magnitude of the ratio may be taken to indicate and to measure specificity in soil colloidal matter.

Table III. Relationship between calculated moisture residues at cessation of shrinkage and hygroscopic coefficients of soils of different geological types.

Soil type	1 Linear shrinkage coefficient* (a)	2 Cubical shrinkage coefficient† (C)	3 Specific gravity of plastic soil (S)	4 Vol. (=wt.) of water lost during shrinkage (C/S)=(V)	5 Dry matter in plastic soil (D)	6 Vol. (=wt.) of water lost during shrinkage (100V/D)=(A)	7 Moisture content at point of maximum plasticity‡ (P)	8 Calculated residual moisture at cessation of shrinkage (P-A)=(R)	9 Hygroscopic coefficient§ (H)	10 Moisture shrinkage lag (difference) (P-A)=H
% of oven-dried soil										
Type 1 (a) M 11	2.5	7.3	2.20	3.32	85.0	3.9	17.7	13.8	2.0	11.8
M 13	6.2	17.3	"	7.87	79.9	9.8	25.2	15.4	4.4	11.0
M 9	6.4	18.0	"	8.19	79.2	10.3	26.4	16.1	5.1	11.0
M 4	8.8	24.2	2.10	11.52	74.1	15.5	35.4	19.9	7.1	12.8
M 7	9.6	26.1	"	12.43	72.9	17.0	37.2	20.2	9.5	11.7
(b) Bdl	10.0	27.0	"	12.86	74.8	17.2	33.7	16.5	7.2	9.3
BsS	10.6	28.5	"	13.57	72.8	18.6	37.5	18.9	8.1	10.8
Type 2 A 14	12.9	33.8	2.00	16.90	68.2	24.8	46.6	21.8	10.7	11.1
ATh	12.6	33.1	"	16.55	68.9	24.0	45.1	21.1	11.5	9.6
A 25	12.2	32.2	"	16.10	69.4	23.2	44.1	20.9	12.1	8.8
A 6	12.1	31.9	"	15.95	68.7	23.2	45.6	22.4	12.3	10.1
A 10	12.9	33.8	"	16.90	67.0	25.2	49.1	23.9	12.7	11.2
A 24	12.1	31.9	"	15.95	71.0	22.4	40.9	18.5	10.2	8.3
Type 3 A 21	13.8	35.6	2.00	17.80	68.6	25.9	46.2	20.3	10.9	9.4
A 41	12.1	31.9	"	15.95	69.4	22.9	44.1	21.2	13.4	7.8
A 13	13.6	35.2	"	17.60	66.7	26.4	49.8	23.4	13.5	9.9
A 46	11.2	29.9	"	14.95	68.1	21.9	46.9	25.0	14.1	10.9
Type 4 (a) D 1	10.7	28.8	1.73	16.05	64.8	25.7	54.5	28.8	15.5	13.3
D 2	13.2	34.4	"	19.88	62.8	31.7	59.3	27.6	17.8	9.8
BaR	13.9	35.9	"	22.83	63.7	35.6	57.2	21.6	16.6	5.0
BsR	8.6	23.6	"	13.64	67.2	20.3	48.8	28.5	20.6	7.9

* Means of five replicates. Mean probable error for $a = \pm 0.18$. † Calculated from the formula $C = 3a - (3a^2/100)$.

‡ Means of five replicates. Mean probable error for $P = \pm 0.26$. § Means of five replicates. Mean probable error for $H = \pm 0.23$.

III. The suggestiveness of the data in Table II led to an attempt to calculate residual moisture contents from observed shrinkage coefficients for soils belonging to the four main types, and including samples of varying mechanical constitution. The results are recorded in Table III. The calculation of the amount of water lost during shrinkage (column 4) involves a knowledge of the specific gravities of the plastic soils. These cannot be determined on the actual blocks used in the shrinkage experiments; the figures in column 3 are means of determinations made on separate lumps of the plastic soils by an oil-displacement method. It is assumed in calculating the moisture residues that the whole of the water in the soil blocks is colloiddally imbibed water.

The computed values for moisture residues at cessation of shrinkage, expressed as percentages of the mass of the oven-dried blocks (column 8), are in considerable excess of the hygroscopic coefficients of the soils. On the whole, however, this difference is fairly constant, and, in the case of the more colloiddal soils, is approximately equal to 20 per cent. of the total imbibed water. Variations in its magnitude may be assigned to three main causes, namely: (1) inaccuracies introduced in calculating cubical shrinkage coefficients from linear coefficients; (2) the presence of free water (in contradistinction to colloiddally-imbibed water) in the plastic soil block, which, especially in the case of the less colloiddal soils, renders the figures for total quantity of imbibed water (column 8) too high; (3) to shrinkage lag whereby the volume changes during the last stages of contraction are in considerable deficit of the volume of water lost⁽¹⁴⁾. The last-named cause is obviously the most efficacious of the three. The mechanism of shrinkage lag will be fully discussed elsewhere. Its incidence is a disturbing factor which prohibits the employment of shrinkage measurements as a means of indirectly estimating the hygroscopic coefficients of soils.

IV. Foregoing considerations have suggested that the colloiddal matter of soils, when fully saturated, contains its water in two phases, and that the ratio of the quantity of water representing these phases varies for soils of different geological origin. It was thought desirable further to test these conclusions by isolating the clay fractions of the main soil types, and employing this material in redeterminations of the moisture constants.

The results are presented in Table IV. The ratio values (columns 4 and 5) vary similarly to those estimated for the whole soils, and support the conclusion that it is the specific nature of the colloiddal material that accounts for the differences in these ratios.

Table IV. *Moisture constants of the clay fractions of soils of different geological types.*

Soil type	1 Linear shrinkage coefficient* (a)	2 Moisture content at point of maximum plasticity† (P)	3 Hygroscopic coefficient‡ (H)	4 Ratio $\frac{(P)}{(a)}$	5 Ratio $\frac{(P)}{(H)}$
	% on oven-dried soil				
Type 1 (b) Bdl	16.0	61.8	13.1	3.86	4.72
BsS	16.8	69.1	14.5	4.11	4.76
Type 2 A C	19.2	78.4	21.0	4.08	3.73
Type 3 A D	20.0	80.4	22.2	4.02	3.62
Type 4 (a) D 2	14.3	63.2	19.1	4.42	3.31
(b) BsR	10.1	55.7	23.2	5.51	2.40

* Means of duplicates. Blocks of dimensions $3 \times \frac{1}{2} \times \frac{1}{2}$ " were used.

† Ditto.

‡ Means of five replicates.

The oven-dried material of the clay fractions was submitted to ultimate chemical analysis. The analytical data are contained in Table V. The high ratio of $\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ to SiO_2 for Type 4 indicates the lateritic nature of the red soils employed in this investigation. Probably these soils owe their special physical characters mainly to the presence of colloidal aluminium hydroxide(15). The low ratio of $\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ to SiO_2 for Types 1, 2 and 3, indicates that the colloidal matter in these soils resembles more that contained in soils of temperate regions, which is chiefly silica and silicates(15a).

Table V. *Chemical analyses of clay fractions separated from soils representative of the four geological types.*

	Type 1	Type 2	Type 3	Type 4	
Ultimate analysis*	Bdl	Composite sample	Composite sample	D 2	BsR
SiO_2	55.7	57.9	55.8	34.6	39.9
Al_2O_3	15.8	17.0	23.0	28.0	25.7
Fe_2O_3	17.7	9.6	8.2	21.6†	18.2†
CaO	Trace	5.5	1.0	0.1	0.6
H_2O	9.9	9.5	12.7	17.2	15.4
	99.1	99.5	100.7	101.5	99.8
Ratio $\frac{(\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3)}{\text{SiO}_2}$	0.60	0.46	0.56	1.43	1.10

* Method of Clowes and Coleman, *Quant. Chem. Anal.* 1918, p. 126.†, Containing TiO_2 .

SECTION 3. DISCUSSION.

(A). *Moisture content at the point of maximum plasticity.*

Many investigators of the physical properties of clays, besides the West Indian workers already cited, have assumed that the moisture content of a plastic clay at the stage when it can most easily be moulded marks the saturation point of the colloidal material contained therein(16). It is desirable to examine the physical basis of this assumption. As a prerequisite, the meaning of plasticity must briefly be considered.

The usually accepted definition of plasticity is "the property of a substance which enables it to change its shape without rupture when subjected to pressure, the new shape being retained when the pressure is removed(17)." Recent research has shown that plasticity depends on at least two distinct properties, namely, mobility and cohesion(18). In the case of a clay, mobility appears mainly to decide *workability*(19). On the other hand, cohesion gives to the material a definite "yield value"; a shearing force of magnitude less than this will not produce permanent deformation. The plasticities of clays may therefore best be compared by estimating their yield values at constant mobility(19).

As the amount of water in a kneaded clay is increased, the mobility of the material is increased, but the yield value is diminished. This suggests that the plasticity of a clay is largely decided by the state of occurrence of its water content.

In support of this view, the case of plastic wet sands may be considered. It is generally admitted that wet sands owe their plasticity to water-films that bridge the angles between the grains(20). Hence, a feature of plastic wet sands is that they contain air, since their pore spaces are not completely filled with water. The magnitude of the film tension in an ideal plastic sand consisting of uniform spherical grains, varies inversely as the radius of the grains. When this latter factor approaches molecular dimensions, it may no longer be justifiable, however, to express film tension as a function of curvature, for, at this lower limit, the range of molecular attraction is reached, and an additional force is introduced(21). The presence of a solute, dissolved in the water of a plastic sand, exercises a specific effect on the magnitude of the cohesive force, since it directly influences surface tension.

As the water content of a plastic sand is increased, the films progressively vanish; internal cohesion is diminished, and mobility is increased. When the pore spaces become filled with water, the particles

are scattered; the material behaves as a viscous liquid, and the mass may now adhere to external objects.

Plastic clays differ from plastic sands in that the former contain colloidal matter. Comber conceives that the ultimate particles of a clay or soil are coated by a protective layer of colloid, which is of an emulsoid or gel nature, and which, if present in sufficient amount, may dominate the system, and impress its properties on the whole (22). In a later paper (23), Comber develops this conception, and insists that what has been termed the protector of the clay particle is not to be regarded as the mere coating of the particle, but rather as an intrinsic part of it, "merging into less hydrated matter on the one hand, and into water on the other."

That plastic clays contain free liquid, bounded by surface films, is implied in the statement, attributed to Le Chatelier, that all plastic clay masses contain air (24). Frequent mention of this fact is made in ceramic literature, and numerous methods of estimating the "porosity" of plastic clay have been described (25). If the pore spaces of a clay were completely filled with water, the particles would be scattered, and the material would be, in effect, a "clay slip" of finite fluidity.

The magnitude of the film tension in plastic clays is decided, not only by the average radius of the particles, and by the effect of solutes on surface tension, but also by factors introduced by the presence of colloidal matter in the system. Indeed, certain investigators have claimed that plasticity is a direct function of colloid content (26). It is therefore necessary to examine the possible effect which the presence of colloid coatings round the particles of a clay might exert on the tension of the water-films that keep the mass firm.

Wilsdon has equated the forces in equilibrium in moist colloidal soils in contact with a saturated atmosphere, and at a fixed temperature (27). His procedure is based on thermodynamical considerations of the system water-vapour, soil colloid, and free soil solution. His deductions indicate that film tension (F), "swelling pressure" of colloid (S), and osmotic pressure (P) of the soil solution which constitutes the films, are simply related, thus: $F = P - S$. Since swelling pressure is equal in magnitude but opposite in sign to the force of imbibition which causes water to be drawn into the soil colloid, Wilsdon's equation indicates that film tension is greatly *augmented* by the effect of the presence of colloidal matter in a soil, at least during the active imbibition of water (27a).

It appears probable, therefore, that a clay becomes readily workable only when sufficient water has been added completely to saturate the colloidal matter present, for, at this stage, film tension is not affected by

the force of imbibition, and can easily be overcome by the pressure of the hands. The range of workability in fine-grained clays is small, since the addition of a further quantity of water soon fills the pore spaces, and allows exterior adhesion to occur. The clay at this stage is sticky.

The term "point of maximum plasticity," as used by workers in the West Indies, obviously refers to the stage when a clay can most easily be kneaded. It was apparently gauged by noting the point at which the drying material ceased to adhere unduly to the hands. Mason definitely employed this last criterion in standardising the water contents of the soils examined by him⁽²⁸⁾. The writer also accepted the onset of stickiness as marking the saturation stage of the colloid component of clays and soils. In approximate determinations, the experimental and theoretical results submitted in the foregoing discussion appear to warrant the acceptance of the "moisture content at the point of maximum plasticity" as a physical constant representing the imbibition capacity of the colloidal matter present in a clay or soil. A better term would be either "moisture content at the point of optimum workability," or, "at the point of stickiness," or, "at the point of development of exterior adhesion."

In soils of low colloid content (silts and sands), the constant ceases to possess the significance assigned to it, for, in these soils, considerable free interstitial water occurs when exterior adhesion becomes manifest. This fact is brought out by the data already discussed (Table III).

(B). *Shrinkage.*

Shrinkage in clays and soils may be assumed to be the reverse of swelling, which is caused by imbibition of water by the colloidal matter present. The process of swelling in emulsoid colloids has been the subject of a great deal of experimentation and speculation. Its main interest so far has lain in the application of the results and theories to biology⁽²⁹⁾, and to industries such as leather manufacture⁽³⁰⁾. Gelatine is the colloid that has been the most rigorously studied.

According to Posnyak⁽³¹⁾, three explanations of the swelling process are possible. They are: (1) condensation of water on the surface of the elementary particles of the colloid, leading to a filling up of the capillary spaces between them; (2) simple solution of the liquid in the substance of the particles, which thereby change their size, density, etc.; (3) a combination of both these processes. The last is regarded by Posnyak as the most probable one theoretically.

It is important to notice that, in the process of swelling, the total

volume of colloid plus water, is less after swelling, although the volume of the colloid itself increases(32). In order to compress water to the extent implied in the total change of volume(33), a pressure of some 300 atmospheres may be necessary, so that it is evident that heat must be evolved during imbibition. Rosenbohm(34) found that the swelling of gelatine appears to be divisible into two stages; the first in which a small amount of water is taken up, and all the heat is evolved, the second in which a large amount of water is absorbed and no heat evolved. This result supports the third alternative theory of Posnyak. It has considerable moment in connection with swelling phenomena in clays, as will later be indicated.

The various theories adduced to account for imbibition and swelling have led to different concepts of the structure of emulsoid colloids(35). Certain authorities hold that elastic gels are homogeneous systems (Procter, Pauli, Katz); others, that elastic gels are heterogeneous (Ostwald, Bradford, W. B. Hardy, Lloyd), in which one part is a liquid phase, and the other, either a liquid (Ostwald) or a solid phase(36). The consensus of opinion appears, in general, to favour the last-named theory. This theory is really the original "sponge work" theory of Nägeli (1858), which has since been developed by Bütschli (1902) and Zsigmondy (1912), amongst other investigators.

It has been remarked that most of the researches undertaken to elucidate the process of imbibition have been performed with gelatine and other proteins, which are *elastic* gels. It is generally conceded that the colloidal matter of clays and soils is an *inelastic* gel, and is most nearly exemplified by silica gel, of which many physical data have been accumulated, notably by the classical researches of Van Bemmelen. Zsigmondy(37) has pointed out that gel structures may vary greatly, especially in the individual nature and arrangement of the primary particles that constitute the material of the spongework. Gels may also vary in the size of the vesicles enclosed by this reticulate structure, and in the thickness of the walls(38). It appears probable that the solid material of most or all gels is ultimately crystalline(39). As regards the special case of silica gel (and probably of clay and soil colloids in general), it has been suggested that rigidity is due to the fine fibrillar structure of the spongewall(40). Hatschek(41) indicates the possibility of explaining rigidity in terms of internal arrangement, but maintains that a great amount of further research is needed before the known facts can so simply be explained. He lays stress on the observation that silica gel, on drying, may develop pores containing air. These pores may be filled by imbibition

with a liquid other than the liquid originally present in them. Elastic gels apparently do not develop such pores, nor do they exhibit such imbibition phenomena. Hatschek's statements regarding silica gel are based mainly on Patrick's observation (42) that a silica gel containing 5 per cent. of water absorbs a further large quantity of water and swells, because the capillaries become filled with the liquid. His conclusions are supported by the work of Zsigmondy and his school, as described by Anderson, and above quoted. Patrick and Neuhausen (43) have recently investigated the organogels of silica, and have shown that Graham was in error when he stated that it is possible to replace all the water from a silica gel by other liquids. There remains at least 5 per cent. of water which is held by great force. Heating to 300° C. *in vacuo* for six hours fails to reduce the content of water below 4.8 per cent., but, at the same time, it leaves unaltered the ability of the gel to imbibe water.

A new method, elaborated by Parker (44), of extracting the soil solution by adding alcohol to soils, would appear to be, in part at least, an application of the principles involved in these changes. Parker obtained 36 per cent. displacement with a silt loam containing 21 per cent. of moisture, so that a considerable fraction of the liquid imbibed in the soil colloids must have been replaced by alcohol in his experiment. Furthermore, the replaceable liquid of the soil colloids evidently contains dissolved electrolytes present in approximately the same proportion as in the soil solution.

We may now tentatively describe the structure and composition of the colloidal material of clays as follows. Clay colloids are inelastic emulsoid gels with a reticulate structure. Their rigidity is due partly to the particular nature and arrangement of the primary particles of which the walls of the structure are composed, and partly to the size of the vesicles enclosed by these walls. The liquid content of the swollen gel exists in two phases. The first is firmly adsorbed in the material of the walls. The second fills the vesicles, and is probably crystalline, that is, it contains matter in molecular dispersion, or at least, very highly dispersed. Swelling is conceived as being due to two distinct processes: (1) to the adsorption of water by the material of the walls of the reticulate gel, and controlled by the particular nature and physico-chemical behaviour of the wall material, and by the presence or absence of adsorbed ions at its surface, and (2) to an imbibitional force which causes water to be drawn into the vesicles of the colloid.

The properties of the vesicle walls of reticulate emulsoid colloids have not yet been thoroughly explored. In certain cases, for example,

gelatine, it appears that the wall material, besides being elastic, is also semi-permeable(45). In the case of silica gel, and of inelastic inorganic colloids in general, the vesicles may be in open communication, both with one another, and with the exterior surface. If this be so, then imbibition into the vesicles of such colloids is merely a process of capillarity (46).

Evidence in favour of the view that emulsoid colloids of soils and clays are reticulate in structure is afforded by Wilsdon's researches, which led him to consider the "bound" water of soils as divisible into "gel" water (i.e. the water adsorbed in the walls of the reticulate colloid), and "vesicular" water. In the soil examined by Wilsdon (a silt-loam from Lyallpur, India), it appears that the bound water in the fully swollen colloid, is divided between these two phases in the ratio of 1 to 3.73. Furthermore, Wilsdon suggests that the gel water is the water which represents the *moisture content at the hygroscopic coefficient stage*. If this be so, then the total bound water of the soil examined must be 4.73 times the hygroscopic coefficient. Wilsdon refers to this ratio by the term "vesicular coefficient (47)."

The data obtained by the writer (Table II, column 8, and Table IV, column 5), indicate that the vesicular coefficient of the colloidal matter of soils of different geological types varies considerably. For soils of Type 1, it is approximately 4.7, and in this, these soils resemble Wilsdon's soil. For soils of Types 2 and 3, it is 3.6, and for those of Type 4 (red lateritic soils), it ranges between 3.5 and 2.4. The most typical lateritic soil is the Barbados red soil (BsR), which has a vesicular coefficient of 2.4.

If we assume that shrinkage is due to loss of vesicular water, as is suggested by the experimental results presented in Table II, it follows that, in drying from the saturated condition down to the stage when the water content of the colloid exists entirely as gel water (hygroscopic coefficient stage), clays and soils will exhibit all their shrinkage effects between these two limits. Further drying in unsaturated air ought not to cause further diminution in volume, nor ought oven-drying to have any additional effect. These conclusions are in accordance with fact.

During the evaporation of the vesicular water, increasing difficulty will be experienced in abstracting the imbibed liquid. The rate of shrinkage of a clay undergoing drying in an atmosphere of constant humidity diminishes therefore as the process approaches completion; the total contraction realised does not, however, depend on the average rate of shrinkage; it is apparently the same in any given sample of clay, no matter whether drying be rapid or slow (48). This fact furnishes an objection to

Tempany's view that shrinkage lag is due to internal friction and inertia of the particles that compose a clay. Furthermore, Tempany's hypothesis does not explain why shrinkage lag should be exhibited by clays whose particles are of strictly uniform size. Clays composed of particles of very varied dimensions might exhibit *warping* due to friction.

The time required for the attainment of maximum shrinkage for any given rate of drying, depends only on the initial water content and the mechanical composition of a clay (48). This fact also is explicable on the assumption that shrinkage is due to the loss of vesicular water.

Tempany's postulation that the colloidal matter of soils exists as a "ramification throughout the mass," precludes the possibility of the occurrence in plastic soils of air in addition to free water bounded by surface films. It also fails to explain cohesion in the less colloidal soils whose particles may not possess coatings of gel material in amount sufficient to effect within the mass complete coalescence and continuity of colloid with exclusion of air.

If it be conceded that the colloidal matter of soils and clays possesses a reticulate structure, shrinkage lag may readily be explained, for it is possible to conceive that a stage is reached during the drying of a plastic clay when the walls of the colloid structure are sufficiently rigid to resist further contraction. Beyond this stage, water loss is accompanied by the intrusion of *air* into the vesicles. That such a result may occur is indicated by the behaviour of silica hydrogel during dehydration (49). A silica gel containing 540 parts by mass of water to 100 parts of anhydrous silica, is a stiff almost transparent jelly. On drying, it loses water continuously and conforms to a smooth dehydration curve. When it contains about 180 parts of water to 100 of silica, the gel is brittle and may be pulverised; when the water content reaches between 90 and 45 parts by mass to 100 of silica, the gel becomes opaque. Up to this point, shrinkage is uniform; below it, shrinkage falls off quite suddenly, until it soon ceases altogether. The opaque state has been shown to be due to the appearance of air bubbles in the gel. At still lower moisture contents, opacity gives place to transparency; the vesicles are now completely filled with air, and the water is present only as an adsorbed phase in the walls of the sponge-work.

It will appear from this account that the hygroscopic coefficient of silica gel should have a value lying between 90 and 45 per cent. of the mass of the dry substance. It is of interest therefore to note that Beaumont (50) gives the figure 58.1 for this constant for silica gel prepared by artificial means.

Gelatine jelly behaves dissimilarly to silica gel, owing possibly to the fact that the walls of the colloid structure are not rigid, so that, during drying, they collapse completely, leaving no internal air spaces (51).

Silica hydrogel is usually considered to be an irreversible gel, in that its behaviour on successive drying and moistening is not strictly concordant. This fact has been explained as due to the difficulty of expelling the entrapped air of a silica gel that has once been dried (52, 53). Apparently also repeated drying and wetting affects in some measure the adsorptive properties of the *wall* material of soil colloids, for Beaumont has shown that the hygroscopic coefficient and the retentivity for dyes of the colloidal matter of certain soils is thereby diminished (54).

(C). *Specificity in soil colloids.*

It appears probable that the colloidal matter of soils of different geological origin and chemical composition are specific in certain of their properties. Evidence in favour of this view is rapidly being accumulated. By such means as centrifugation, it ought to be reasonably easy to isolate the colloidal material from clays and soils of different types, and thus to render possible the systematic examination of naturally-occurring colloids by modern physical methods. A start in this direction has already been made at the Bureau of Soils of the United States of America (55). Many of the apparent anomalies in the behaviour of soils and clays may be satisfactorily explained on the assumption that colloids exhibit differences in their several physical constants, in particular, in the ratio between the amounts of gel water and of vesicular water which a given mass of the dry colloid is able to imbibe. Recognition of this possibility enables one to explain irregularities such as those remarked by Mason and by the writer for certain red soils of the West Indies, and by Tempany for certain soils of Mauritius (56). Differences in structure may in this way account for differences in the manner in which various soil colloids hold water.

The fact must not be overlooked, however, that theories other than the above have been propounded to account for what we may tentatively describe as specificity in colloidal gels. Thus Sheppard and Elliot (57) have recently suggested that the different shrinkage maxima exhibited by blocks of aqueous jellies, containing various concentrations of gelatine, are due, not primarily to structure, but to changes in shape which cause unequal distribution of water, and which result in a sort of "case-hardening" at the exposed edges and corners of the drying mass. This limits contraction to a degree depending mainly on the initial water

content. The view is not incompatible with the two-phase theory of gel structure, as the authors admit, provided we assume that the structure elements of the wall material are not inherent to, or characteristic of, a particular colloid, but are the resultants of physico-chemical changes of environment.

Sheppard and Elliot's suggestion indicates the possibility of explaining specificity of inorganic soil and clay colloids in terms of geological genesis and history (58), rather than of chemical character. Viewed in this aspect, the theory is more in keeping with the fundamental conception of colloids as matter in a particular *state*, rather than distinct *kinds* of matter of varied individuality. Recent researches on gels, both organic and inorganic, are rapidly leading to a recognition of the fact that specificity in these colloids is conditional and structural rather than absolute. The individual characters of gels can probably all be accounted for on the assumption that, in gel formation, "there is a linking of the elements of one phase into some continuous structure. Whether this consists of single filaments, of strands or fibrils,...or of crystals twinned, or otherwise interlinked, must be left open" (59).

SUMMARY.

1. The investigation described is a continuation of the researches of certain workers in the British West Indies on the significance of the shrinkage coefficient of clays and soils. A brief outline of these researches and their results is given.

2. Tempany's hypothesis, which explains shrinkage as due to contraction consequent on loss of water by evaporation from the saturated gel-skeleton that ramifies throughout a mass of soil at its point of maximum plasticity, is criticised on the grounds that it does not completely fit the facts. In particular, it fails to account for the abnormally low shrinkage coefficients exhibited by lateritic soils, notably the red upland soil of Barbados. Mason explained this abnormality by assuming that kneading does not entirely destroy aggregation of soil particles, which is especially well marked in the Barbados red soil. The writer demonstrated, however, that soils of similar colloid content, and belonging to one and the same geological type, but exhibiting different degrees of aggregation, possess similar shrinkage coefficients. A different hypothesis to explain soil shrinkage was therefore sought.

3. The hypothesis finally accepted is based on the belief that colloidal gels possess a reticulate structure. At the point of saturation, a hydrogel

probably contains water in two phases. The first of these is adsorbed in the walls of the gel; it has been shown by Wilsdon, in the case of soil colloids, *to represent the moisture content at the hygroscopic coefficient stage*. The second phase fills the vesicles of the gel, and is a crystalline phase.

4. The writer demonstrated that shrinkage in clays and soils is due solely to loss of vesicular water.

5. Tempany has shown that cubical contraction is numerically equal to volume loss of water during the earlier stages of shrinkage. During the later stages, a marked shrinkage lag occurs. This is explained by Tempany as due to friction and inertia of the particles; it is, however, more probably due to the rigidity of the walls of the vesicles which do not completely collapse during drying. Loss of water during the later stages of shrinkage is accompanied by intrusion of air into the vesicles. Accurate values for the hygroscopic coefficients of soils cannot, therefore, be calculated from observed shrinkage coefficients.

6. Variations in the shrinkage coefficients of soils of similar colloid content, but belonging to different geological types, are probably due to specificity in soil colloids. This manifests itself chiefly in differences in the ratio of adsorbed (hygroscopic) water to vesicular water. Red lateritic soils, rich in alumina hydrogel, appear to possess relatively low vesicular water contents, and in consequence, to exhibit low shrinkage coefficients.

7. The physical basis of the assumption that the "water content at the point of maximum plasticity" represents the imbibition capacity of a clay or soil is discussed in the light of modern theories of plasticity. This constant may provisionally be accepted as marking an important stage in the water relations of clays and soils. Its terminology is open to criticism; alternative titles are suggested.

. The writer wishes to acknowledge indebtedness to B. H. Wilsdon, Esq., for many valuable suggestions; to his colleague, T. G. Mason, Esq., and to Sir E. J. Russell and Dr B. A. Keen, of Rothamsted, for criticism of the original draft of this paper.

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REFERENCES.

- (1) If a be the linear coefficient, and C the cubical coefficient of shrinkage, then

$$C = 3a - \frac{3a^3}{10^3} + \frac{a^3}{10^4}.$$

- (2) See AUCHINLECK. *West Ind. Bul.* 1912, 12, 50.
 (3) *Ibid.*, footnote by TEMPANY.
 (3 a) *Ibid.* pp. 54, 55.
 (4) *Journ. Agric. Sci.* 1917, 8, 312.
 (5) *West Ind. Bul.* 1922, 19, 125.
 (6) HARDY, F. *Ibid.* 1922, 19, 189.
 (7) TEMPANY. *Ibid.* 1915, 15, 69.
 (8) HARRISON and JUKES-BROWNE. *Geol. of Barbados*. Expln. of map, 1890.
 (9) *Bul. Mus. Roy. Hist. Nat. Belg.* 1884, 3, 273. See SPENCER, *Quart. J. Geol. Soc. London*, 1901, 57, 490, and BROWN, *Proc. Acad. Nat. Sci. Philadelphia*, 1913, p. 584.
 (10) HARDY, F. *West Ind. Bul.* 1921, 19, 86.
 (11) HARRISON and JUKES-BROWNE. *Quart. J. Geol. Soc. London*, 1891, 47, 197, Pt I.
 (12) HARRISON. *Ibid.* 1920, 75, 158, and *West Ind. Bul.* 1920, 18, 77.
 (13) See Section 3, Discussion.
 (14) See TEMPANY's shrinkage curves. *Journ. Agric. Sci.* 1917, 8, 320.
 (15) The origin of red soils has been investigated by Manasse in Sienna (*C.A.* 1917, 11, 1510), who proved that a large part of the Al_2O_3 , almost all the Fe_2O_3 , and a small proportion of the SiO_2 are present as colloidal material. According to Wiegner (*C.A.* 1917, 11, 1707) tropical red soils contain colloidal Al_2O_3 and Fe_2O_3 , whereas tropical yellow soils contain colloidal Al_2O_3 and SiO_2 chiefly. The Dominica red soil (D 2) would thus appear to be related to the first group, and the Barbados orange-red soil to the second. Highly dispersed Fe_2O_3 , however, is known to possess a yellow colour, whilst the less-highly dispersed substance has a deep red tint. (See WEISER, *C.A.* 1920, 14, 2738; YOE, *Ibid.* 1921, 15, 2026 and BRADFIELD, *J. Amer. Chem. Soc.* 1922, p. 965.)
 (15 a) Comber's experiments (*Journ. Agric. Sci.* 1920, 10, 425 and *Ibid.* 1921, 11, 450), identify the major colloidal component of siliceous soils as SiO_2 . His quantitative test for clay "fatness" (*Journ. Soc. Chem. Ind.* 1922, 41, 77), further supports this conclusion.
 (16) ROHLAND. See Searle, *Third Rept. Colloid. Chem.* London, Dept. Sci. and Indus. Res. 1920, p. 133. Also ATTERBURG, *Int. Mitt. Bodenk.* 1911, p. 37.
 (17) REIS. *Clays*, 1908, p. 119.
 (18) BINGHAM. *Fluidity and Plasticity*, 1922, Chap. VIII.
 (19) WILSON, R. E. and HALL. *Journ. Indus. Engin. Chem.* 1922, 14, 1120. Also, BINGHAM, BRUCE and WOLBACH. *Ibid.* p. 1014.
 (20) See BANCROFT. *Applied Colloid Chem.* 1921, pp. 154-160.
 (21) TROUTON. *Proc. Roy. Soc. A*, 1905, 77, 292.
 (22) *Journ. Agric. Sci.* 1920, 10, 425.
 (23) *Ibid.* 1921, 11, 450.
 (24) SEARLE. *Third Rept. Colloid Chem.* 1920, p. 126.

- (25) See, for example, SPURRIER, *Journ. Amer. Ceram. Soc.* 1918, **1**, 710. Also, *Ibid.* 1922, **5**, 34.
- (26) For example, ASHLEY, *U.S. Geol. Survey, Bul.* 388, 1909.
- (27) *Mem. Dept. Ag. India, Ag. Res. Inst. Pusa*, Chem. Ser. **6**, 3, March, 1921.
- (27 a) The effect on plasticity of adding solutes to clays has been extensively investigated by ceramists. The main facts are summarised by SEARLE (*Third Rept. Colloid Chem.* 1920, pp. 125, 126, etc.). If a plastic clay owes its properties to interactions between film tension, imbibition force, and osmotic pressure, the addition of a solute may bring about an increase or a decrease in plasticity in accordance with the specific effects which the added substance exerts on these factors. Solutes already present in a clay must not be left out of account, nor should one ignore the possibility of peptisation which might lead to partial disintegration of the colloid, nor the specific action which hydrogen-ion is believed to exert in swelling phenomena. (See SMITH, *Journ. Amer. Chem. Soc.* 1921, **43**, 1350; HENDERSON, *Ibid.* 1918, **40**, 858; the work of PROCTER, FISCHER, LLOYD, etc., on the relation between swelling and reaction in proteins, which are ampholytes.) O. ARRHENIUS (*Journ. Amer. Chem. Soc.* 1922, **44**, 521), has shown that certain clays are also amphoteric; nevertheless, reaction appears not markedly to influence the mobility factor in plasticity (WILSON and HALL, *Journ. Indus. Engin. Chem.* 1922, **14**, 1120).
- (28) *West Ind. Bul.* 1922, **19**, 128.
- (29) BAYLISS. *Second Rept. Colloid Chem.* 1918, p. 117.
- (30) PROCTER. *First Rept. Colloid Chem.* 1917, p. 5.
- (31) Quoted by BAYLISS, *Principles of Gen. Physiol.* 1920, p. 101. See also BARTELL and SIMS, *Journ. Amer. Chem. Soc.* 1922, **44**, 289, for a general discussion of swelling.
- (32) BAYLISS. *Ibid.* p. 100.
- (33) Experiments with *Laminaria*.
- (34) Cited by WILSON, *Third Rept. Colloid Chem.* 1920, p. 59. PATRICK and GRIMM (*Journ. Amer. Chem. Soc.* 1921, **43**, 2144), have recently determined the heat of swelling of silica hydrogel in water.
- (35) Rept. of Discussion by Faraday Soc. and Phys. Soc. London, Oct. 1920. *Dept. Sci. Indus. Res.* Section 11, 1921.
- (36) *Ibid.* p. 38, Hatschek.
- (37) *Ibid.* p. 51. See also HARRISON, *Ibid.* p. 57, and ZSIGMONDY, *Z. Physk. Chem.* 1921, **98**, 14. See C.A. 1921, **15**, 2571.
- (38) See BARRATT, *Discussion Rept.* p. 50, and ANDERSON, *Ibid.* p. 56. Also BOGUE, *Journ. Amer. Chem. Soc.* 1922, **44**, 1343, for a survey of the theories of the structure of elastic gels.
- (39) ZSIGMONDY. *Discussion Report*, p. 51. Also BRADFORD, *Ibid.* p. 45.
- (40) BARRATT, *loc. cit.* See also BARRATT, *Chem. Age.* 1920, **3**, 473.
- (41) *Discussion Rept.* p. 58.
- (42) See RIDGAL. *Ibid.* p. 55.
- (43) *Journ. Amer. Chem. Soc.* 1921, **43**, 1844.
- (44) *Soil Sci.* 1921, **12**, 209
- (45) See SMITH, *Journ. Amer. Chem. Soc.* 1921, **43**, 1350, who explains the swelling of gelatine as a result of osmosis. Also TOLMAN and STEARN, *Ibid.* 1913, **35**, 317;

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- and 1918, **40**, 264. An account of the relation between osmotic pressure and swelling in colloidal gels is given by WO. OSTWALD, *Handbook of Colloid Chem.* 1918, p. 261.
- (46) The researches of PARKER (*Soil Sci.* 1921, **12**, 209; and *Ibid.* 1922, **13**, 43) lend some support to this view.
- (47) BOQUE (*Journ. Amer. Chem. Soc.* 1922, **44**, 1343) has suggested that gelatine gels contain water in two distinct phases. According to Von Schroeder (see BANCROFT, *Applied Colloid Chem.* p. 75) the ratio between gel water and vesicular water in a fully swollen gelatine gel is approximately 1 to 1.5. The total bound water which dry gelatine can absorb is about seven or eight times its own volume (SMITH, *Journ. Amer. Chem. Soc.* 1921, **43**, 1350), whereas soil colloids probably absorb less than their own volume of water.
- (48) GELLER. *Journ. Amer. Ceram. Soc.* 1921, **4**, 282.
- (49) VAN BEMMELLEN, cited by BANCROFT. *Applied Colloid Chem.* pp. 246-249, and by ZSIGMONDY, *Chem. of Colloids*, 1917, pp. 142-152.
- (50) *Cornell Univ. Ag. Exp. Sta. Mem.* 21, 1919, p. 501. MILLER (*Chem. Met. Engin.* 1920, **23**; *C.A.* 1921, **15**, 969), gives the figure 41 per cent. as the approximate amount of water adsorbed as vapour by colloidal silica.
- (51) BANCROFT. *Op. cit.* p. 243.
- (52) BANCROFT. *Op. cit.* p. 249.
- (53) In view of the possibility of porosity in oven-dried blocks of kneaded clay being partly due to the emptying of the vesicles of the semi-rigid colloid structure during loss of water, the relationship between pore space and shrinkage deduced by TEMPANY (*Journ. Agric. Sci.* 1917, **7**, 312, Pt II) would appear to be irrelevant, or to require a different explanation.
- (54) BEAUMONT. *Cornell Univ. Mem.* 21, 1919, pp. 505-507.
- (55) MOORE, FRY and MIDDLETON. *Journ. Ind. Engin. Chem.* 1921, **13**, 527.
- (56) In a letter to the writer (Jan. 1922) Dr Tempany admits difficulty in correlating shrinkage coefficient with colloid content as determined by degree of adsorption of ammonium-ion, in certain Mauritius soils. He assigns the difficulty to a "peculiarity in these soils," but does not state their geological relationships, beyond indicating that they contain "very large quantities of easily-soluble iron." The soils thus resemble the red lateritic soils examined by the writer.
- (57) *Journ. Amer. Chem. Soc.* 1922, **44**, 373.
- (58) See *Bul. Geol. Soc. Amer.* 1920, **31**, 401; and Rept. of Committee controlling researches on the geology of sediments, *U.S. Geol. Survey*, Appendix C, Apr. 1922.
- (59) HATSCHKE. *Introd. to Phys. and Chem. of Colloids*, 1922, p. 130.

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WATER DISPLACEMENT OF SOILS AND THE SOIL SOLUTION.

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(With One Text-figure.)

NUMEROUS studies in this laboratory and elsewhere have demonstrated the utility of water extractions for many purposes in soil investigations. Except in the case of so-called alkali soils, large amounts of water extractable matters usually connote productiveness in soils although the converse is not necessarily true. The productiveness of many sandy soils, for instance, is difficult to correlate with their water extracts and we must perforce conclude that with the great root development characteristic of growth in sands the low concentrations thus inferred are adequate or that low concentrations are *per se* adequate, if continuously maintained. Apart from such inconsistencies, which it is not our present purpose to discuss, the method of water extraction, involving as it does the use of much larger quantities of water than the soil contains, is open to the objection that it unquestionably removes more or less of certain constituents than are contained in the water of the soil as it exists under conditions favourable to plant growth. In short, the water extract is imperfectly representative of the conventional soil solution and any method which offers more promise in this respect deserves very careful consideration. Among such methods the oil pressure method of Morgan (10) and the hydraulic press method of Lipman (9) need further study as applied to soils continuously maintained under controlled conditions, although the work of Burgess (5) partially covers this requirement for the latter method. We are aware of the theoretical objections (11) to the use of high pressures and while alteration of the soil solution is to be expected from such pressures it is not at all certain from *a priori* considerations that this would be of substantial magnitude.

A very serious objection and one which applies to most of the methods which have been suggested presents itself in the time necessary to obtain solutions from soils containing any considerable amount of colloidal

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matter. For while it is true that some soils may remain substantially unchanged for long periods, we have abundant evidence that important changes may take place within a relatively short space of time. It is even possible that a soil's effective solution may attain a relatively constant total concentration as measured by freezing point depression or conductivity, while undergoing extraordinary changes in the concentration of its solutes, notably in its bicarbonate and nitrate content.

Recently, F. W. Parker, by limiting his work to soils of low colloid content, has obviated this objection, and using a simplified technique and equipment obtained solutions which he designates the soil solution (12). Certain of the facts brought out in his work are so suggestive as to appear to justify further intensive studies of displacement methods in general.

GENERAL CONSIDERATIONS.

Equilibrium is probably never attained in moist soils and even if it were to exist in a given system it is highly improbable that the concentrations of individual solutes would be identical throughout the soil film as long as there is a reserve supply in the soil particle or in colloidal complexes. Since these are practically universal conditions, it follows that solutions obtained from soils merely represent average concentrations. Determination of average concentrations, however, should reveal the potentialities of soils and thus justify the continuance of the use of the term soil solution. This expression will therefore be used in our subsequent discussion.

If water is placed on top of and allowed to percolate through a mass of moist soil in a loose state of aggregation, such as that in which it exists in the field under conditions favourable to plant growth, successive portions of the liquid obtained will be decreasingly concentrated until a low and comparatively uniform level is reached. No one of these portions can properly be assumed to represent the soil solution and the concentration of the entire solution so obtained will doubtless approximate that of a water extract obtained with similar proportions of water and soil. If, however, a similar mass of soil is pressed tightly in a container and treated with ethyl alcohol the successive portions of solution have equal concentrations until the displacing agent begins to appear. Similarly, if a non-miscible liquid is used, the successive portions of liquid obtained would probably have equal concentrations, but apparently the soil must be compacted to a much greater degree (12)¹. Successive portions of equal concentration obtained by either class of procedure are apparently free

¹ See pp. 212 and 215 of citation.

from the probability of contamination or dilution by the liquid used in removing them, but the question remains—do these constitute the soil solution either as it exists in the soil's compacted condition in a tube or as it would exist in its natural state in the field?

According to Parker, his solution may be obtained with any one of a number of displacing liquids, but these vary to a considerable degree in their efficiency⁽¹²⁾¹, i.e. in the proportions of the total moisture of the soil obtained before contamination and dilution by the displacing liquid occurs. Assuming the correctness of this we have in our work used water as the displacing liquid because of its many and obvious practical advantages, in spite of the reputed lower yield of unchanged solution as compared with that obtainable with alcohol.

PRELIMINARY OBSERVATIONS.

In order to satisfy ourselves as to the practicability of obtaining successive portions of solution of constant composition and in sufficiently large amounts to permit of thorough study, a number of preliminary experiments were performed.

A set of such experiments utilised mixtures of pure silica sand with nutrient culture solutions of known composition. One such experiment in which the mixture contained 10 per cent. of moisture, packed in a glass tube and covered with distilled water, gave six successive portions of 13 c.c. each of identical total concentration within the limits of experimental error. This was equivalent to 78 per cent. of the total moisture content of the sand-solution mixture. A similar experiment in which the proportion of nutrient solution was reduced so that the sand contained only 4 per cent. of moisture, was covered with water containing NaCl. No Cl appeared in the solutions drawn off until these amounted in volume to more than half of the moisture in the sand-nutrient solution mixture.

From such mixtures the solutions pass by gravity almost as rapidly as the collecting containers can be replaced, and there is little opportunity for diffusion to take place. Indeed, if the mixtures had been up to the saturation point of the sand or if the sand had been tightly compressed at the lower moisture content there is little doubt but that the yield of unchanged solution could have been materially increased and would perhaps have approximated 100 per cent. recovery. The fact that such a low content as 4 per cent. of moisture in such a mixture could be recovered to the extent of 50 per cent. without evidence of admixture from the displacing liquid when the sand was not greatly compacted,

¹ See p. 213 of citation.

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seemed to offer much promise of the recovery of amounts of solution adequate for precise examination from at least the lighter textured natural soils at the materially higher moistures characteristic of their optimal water requirements.

Additional experiments with small quantities of soils showed, as emphasised by Parker, that the essential element in obtaining successive solutions of equal concentration is a proper preliminary packing of the soil.

An obvious result of the compacting of the soil is to slow up the rate of displacement of solution, which may become so low in many soils as to afford abundant time for the intervention of biological changes before adequate quantities of displaced solution are obtained. By the use of a positive air pressure, from 0 to 100 pounds per square inch, at the surface of the displacing liquid, we have been able to hasten the displacement materially.

EQUIPMENT AND TECHNIQUE.

A battery of soil filtration tubes with air pressure equipment used for filtering soil extracts was adapted to our purpose by the simple expedient of replacing the (Briggs) tubes carrying filter candles by brass tubes of the same cross section as the upper part of the old tubes and of the same length. This gave us a tube of approximately 3 inch diameter and 17 inch length, the cap arrangement at the ends being the same as that of the Briggs tubes with the omission of the rubber nipple at the lower end. Prior to packing with soil a closely fitting brass screen was dropped into the tube and rested on the bottom plate. The screen was then covered with a filter paper of equal diameter. These tubes, to a height of approximately 10 inches, hold 2 kilos of compacted moistened soil leaving seven running inches to serve as a reservoir for the displacing liquid and as a guide for the packing rod. This latter was a piston-like arrangement of wood, the lower end of which fitted closely into the brass tube, the upper end being of smaller diameter and serving as a handle. Most of our experiments were carried out with 2 kilos of moistened soil and 400 c.c. of displacing water. The proportion of displacing water to soil was, of course, arbitrary, but in all cases more than sufficient to furnish an adequate supply of displaced solution and to fill up the pores of the soils, when these were of low initial moisture content.

In filling a tube about 100 g. of soil were added at a time. This was then tamped lightly with the smaller end of the packing rod, after which the rod was reversed and the soil pounded with vigorous strokes. When

the soil was all in the tube the displacing water was placed on top and the tube screwed into the flange of the pressure equipment in the same manner as is customary in using the Briggs filtering apparatus. In a few cases with the lighter soils at high moisture content the solution would begin to drop without the use of artificial pressure, but more pressure was generally necessary and in the case of silty clay loams at low moisture content our maximum possible pressure of 100 pounds was usually required.

The soils used were from the reserve supplies of those described in many of the studies emanating from this laboratory. They had, however, been kept for some years in closed bins and on this account had a relatively higher content of soluble matters than those portions which have been cropped or than the original masses of soil of which they comprised a part. The numbering is, however, the same, and their descriptions and properties may be obtained from numerous publications (3, 4, 6, 14). Some of these were also used by Burgess in his study of the hydraulic pressure method (5).

CONSTANCY OF COMPOSITION OF SOLUTIONS.

The first criterion to apply to displaced solutions is clearly that of constancy of composition. Of course, constancy of composition in successive portions is not alone sufficient to prove that we are dealing with the true soil solution, since we can reasonably conceive that the solution actually obtained comes from the outer layers of the soil film, which even at equilibrium might be sensibly less concentrated than the soil solution as a whole. There is also the further though less probable possibility that successive portions of the actual soil solution are equally diluted by the water used in displacement. Diminishing concentrations, however, would indicate dilution by displacing water and vitiate the conclusion that any portion, even the first, constitutes the soil solution, since division of the first portion into still smaller increments might confirm the fact that it also had been diluted.

To determine the concentration of solution we have used the depression of the freezing-point in our earlier experiments but latterly and for the most part have used the electrical conductivity. The following data are from an experiment with a sandy loam soil, known as No. 11 (Bin) in this laboratory. Its optimum moisture content for plant growth is about 17 per cent. but at the time of displacement it contained only 13.6 per cent.

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⁸⁶ Table I. *Freezing-point depressions of successive portions of displaced solution from Soil 11 (13.6 per cent. Moisture).*

Portions of solution		Δ °C.	Portions of solution		Δ °C.
1	5 c.c.	·142	16	5 c.c.	·136
2	"	·139	17	"	·139
3	10 "	·140	18	"	·121
4	"	·143	19	"	·103
5	"	·138	20	"	·093
6	5 "	·145	21	"	·076
7	"	·147	22	"	·048
8	"	·148	23	"	·040
9	"	·144	24	"	·027
10	"	·150	25	"	·022
11	"	·153	26	"	·017
12	"	·143	27	"	·015
13	"	·141	28	"	·014
14	"	·158	29	10 "	·006
15	"	·140	30	16 "	·010

The successive portions constitute a very uniform series down to the 17th, having due regard to the imperfections of the freezing-point method. Most of the determinations being within the usually assigned experimental error of \pm .005 for Δ . These seventeen portions represent 100 c.c. of solution out of a possible 136 c.c. (1 kilo of soil, 13.6 per cent. moisture) if all of the water of the soil had been removed, or a recovery of 73.5 per cent. of apparently undiluted solution. These results confirm similar data by Parker and are even more cogent having in mind the higher concentration of this particular soil. It would appear to be a relatively easy matter therefore to obtain a high yield of solutions of uniform concentration from sandy soils by displacement with water.

The results were not so satisfactory with silty clay loam soils and dilution of the solutions usually became evident when the volume collected represented a smaller proportion of the initial water content of the soil. On the assumption that some soils would probably give a lower yield than that obtained above, it was decided in the interest of uniform procedure to limit the number of increments of solution collected to 12.5 c.c. portions, or a total of 60 c.c. Such an amount from 2 kilos of soil containing 7.0 per cent. moisture would represent a 43 per cent. recovery which it seemed probable might be recovered from most soils. Since 7.0 per cent. is less than half the optimum moisture content of any of our soils it seemed probable that unchanged solutions might reasonably be expected up to and including the twelfth portion from soils as low as half optimum moisture content.

Considerable preliminary work showed that duplicate experiments were not always consistent with each other. Thus, from a number of

tubes, constant concentrations of successive increments of solutions might be obtained while an occasional tube showed dilution from the start or at an early stage. Such sporadic failures are clearly due to channelling of the core of packed soil caused by irregularity in packing and appear to be unavoidable. We adopted the practice, therefore, of carrying out all experiments in quadruplicate, of measuring the conductivities of various increments of the solutions from all tubes and if these proved consistent, the solutions were used for analysis, but if the solutions from any tube were inconsistent among themselves, they were not analysed.

The following table indicates the kind of results likely to be obtained from the two types of soil studied.

Table II. *Specific Resistances (ohms) of Comparable Solutions.*

		SANDY LOAM								SILTY CLAY LOAM							
		Soil 8 (Bin)								Soil 5 (Bin)							
		14.8 % moisture				7.3 % moisture				18 % moisture				9 % moisture*			
Tube		A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	
1st	5 c.c.	201	201	202	206	103	99	100	102	382	451	375	336	176	159	149	
2nd	"	206	—	—	—	104	—	—	—	498	609	—	—	—	162	—	
3rd	"	202	—	—	—	103	—	—	—	507	577	—	—	—	166	—	
4th	"	206	—	—	—	103	—	—	—	436	558	—	335	—	164	—	
5th	"	206	—	—	—	102	—	—	—	411	515	343	—	—	167	—	
6th	"	204	215	208	206	103	102	104	103	384	439	—	—	180	168	154	
7th	"	206	—	—	—	103	—	—	—	379	409	—	—	—	170	—	
8th	"	206	—	—	—	108	—	—	—	360	379	—	326	—	169	—	
9th	"	206	—	—	—	104	—	—	—	351	368	338	—	—	169	—	
10th	"	204	—	—	—	104	—	—	—	331	352	—	—	—	172	—	
11th	"	206	—	—	—	106	—	—	—	340	343	—	—	—	172	—	
12th	"	206	206	204	211	107	106	104	106	360	347	—	—	185	173	157	

* Tube D of this series was lost.

We here observe an extraordinary consistency in the specific resistances of successive portions of solution from the sandy soil. These results appear to be typical of the lighter soils. Duplicate tubes uniformly give solutions of equal and constant concentration. Such extraordinary consistency obviates the necessity for further determinations of specific resistance and validates all of the solutions for chemical examination.

The silty clay loam soil shows typical variations both in the lack of uniformity as between tubes and in the successive portions from a given tube. There is, however, no evidence of successive dilution and the general magnitudes of the specific resistances are of the same order at each moisture content. Whatever the cause of these aberrations in the results from the more colloidal soils and whatever the significance to be attached to the more consistent results from sandy soils, we may, for the present

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at least, infer that all such solutions bear a similar, though not necessarily identical, relation to the soil solution so-called.

SOLUTIONS OBTAINED WITHOUT DISPLACING LIQUID.

We early observed that many soils at optimum moisture content would yield a few drops of solution when packed in tubes without the application of any displacing liquid. It occurred to us that the amount of such solution might be increased by a slight positive pressure to a quantity capable of having its properties measured and thus serve as a valuable check on solutions obtained when the displacing water was used. Obviously such a solution would be free from the possibility of dilution. Applying slight air pressures (10–15 lbs.) to the surface of soils packed, but without displacing liquid, frequently yielded two or three—5 c.c. portions from sandy soils at optimum moisture and one—5 c.c. portion from silty clay loams at optimum. At half optimum no solution could be obtained in this manner from any soil.

MOISTURE CONTENT AND PREPARATION OF SOILS.

The condition of the soil at optimum moisture for plant growth obviously deserves first consideration in studies of soil fertility. In studies of the soil solution, the condition of the soil at other moisture contents, higher or lower than optimum, are desirable for comparative purposes and to determine the effect of the gains or losses of moisture to which natural soils are universally subject. Having in mind a proper limitation of our work in a preliminary study, it seemed that moisture contents of approximately optimum and half optimum would meet our requirements, and these have been used in this work.

In preparing soils for study at different moisture contents, we at once confront the practical difficulty of securing uniform distribution of any added water and at the same time avoiding the complications arising from biological activities stimulated by the changed environment during the period necessary to bring the new water-soil system into equilibrium.

If we add water to very dry soils, the major biological effect to be expected would be increased nitrification (provided the added water does not greatly exceed the amount necessary to bring the soil to optimum for plant growth). Seriously to vitiate the results of observations on solutions obtained from such moistened soils, within a limited period, the rate of formation of nitrates would not only have to be very high, but would have to be very different at the various moisture contents studied.

Our method of preparing the soils was as follows:

A mass of mixed air-dry soil (usually about 3 per cent. mo was divided into two portions. Each portion was placed in its contain^t (earthenware crock) by adding successively small amounts of soil and water until the jar was full, and the average moisture content (of the non-homogeneous mixture) was about 2 per cent. above the optimum or half optimum as the case might be. After 24 hours, soils were screened, mixed, replaced, and sampled for moisture determination. This was repeated the following day and the displacing tubes filled on the third day.

In our view, the character of the results reported hereafter seem to preclude appreciable changes during the preparation of the soils. It is possible, however, that soils containing very small amounts of nitrates, in which the inhibiting effect of high concentrations of nitrates is absent, might require a different method of preparation.

The displacement of the soil at optimum was commenced as soon as the water was uniformly distributed in the soil. Soils at half optimum, if at all colloidal, must be allowed to stand with water on top for an additional period (in practice overnight) before pressure is applied. This is an unfortunate difference between the treatments, but cannot be avoided, as otherwise the water will not pass through, or if it does, the soil core channels and the supernatant water simply passes through.

The possibility of denitrification taking place in the packed tubes has been considered, and while there is occasional evidence of this in that successive portions of the solution displaced frequently decrease somewhat, particularly when the duration of the displacement is unduly prolonged, the quantitative change is not greater than is reasonably assignable to experimental error on determinations involving such small titrations and weighings.

CONCENTRATION OF DISPLACED SOLUTIONS.

Tables III A and III B include determinations of freezing-point depressions on the soils themselves, where determinable, as well as depressions and specific resistances of the solutions obtained. Ordinarily the freezing-point depression was made on the first portion of solution only, the comparative concentrations of the successive portions being established by the specific resistances. These latter in each instance were from the results on solutions from that one of the quadruplicate tubes on which the series was completed and are not selected for superior consistency.

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at least
identical

Table III A. *Concentrations of Solutions Displaced from Sandy Loams**.

Soil	Soil 8				Soil 9				Soil 11			
	14.8 % moisture		7.3 % moisture		14.3 % moisture		7.5 % moisture		16.6 % moisture		8 % moisture	
	Δ (° C.)	Specific res. (ohms)	Δ (° C.)	Specific res. (ohms)	Δ (° C.)	Specific res. (ohms)	Δ (° C.)	Specific res. (ohms)	Δ (° C.)	Specific res. (ohms)	Δ (° C.)	Specific res. (ohms)
1st 5 c.c.	-.147	—	-.490	—	-.099	(283)† 276	-.343	—	-.099	—	-.454	—
2nd "	-.130	(199)† 201	-.280	103	-.085	292	-.203	145	-.090	285	-.216	122
3rd "	—	206	—	104	—	289	—	145	—	289	-.193	138
4th "	—	202	—	103	—	287	—	145	-.093	292	-.172	147
5th "	—	206	—	103	—	289	—	144	—	295	-.181	152
6th "	—	204	—	102	—	289	—	143	—	296	-.180	155
7th "	—	206	—	103	-.073	289	-.218	143	-.089	294	-.173	155
8th "	—	206	—	103	—	287	—	145	—	292	-.182	ND
9th "	—	206	—	108	—	287	—	147	—	289	-.175	"
10th "	—	204	—	104	—	282	—	149	-.092	289	ND	"
11th "	—	206	—	106	—	283	—	151	—	283	"	"
12th "	—	206	—	107	-.073	289	-.193	154	-.096	285	"	"
Average		205		104		287		146		289		145

* Solution obtained in a few hours, except from Soil 11 at 8 % moisture where the 9th to 12th portions were collected the 2nd day.

† Solution obtained from a separate tube of soil without the aid of displacing water. (See text.)

SANDY LOAM SOILS.

These data show that sandy loam soils at the higher moisture content give successive solutions of approximately equal concentration. This was also substantially true of two of these at the lower moisture content. The third sand shows somewhat higher concentration in the first portion at low moisture content leading to the inference that the succeeding portions had been somewhat diluted. If, however, dilution is the cause of the higher resistances and the lowered value for Δ , it is remarkable that the second to ninth portions should be so uniform. It is noteworthy that the specific resistances of the portion obtained at the higher moisture content without displacing liquid from Soils 8 and 9 are substantially equal to those observed when displacing liquid was used, which seems to us conclusive that no dilution of the latter by displacing water could have occurred. We may also observe that the average specific resistances of the solutions obtained at different moistures are almost exactly proportional to the initial moisture contents in the case of all of the sandy soils.

This would seem to mean that whatever may be the condition of moisture as it actually exists in these soils, the displaced solutions represent, in their concentrations of electrolytes, the ratio of dissolved material to the total moisture of the soil. So that if water in appreciable amounts exists in these soils in a state which renders it ineffective as a solvent, it would appear either that it is removable by water displacement or that if such unfree water is retained a nearly equivalent quantity of electrolytes is also withheld, and we have in effect unfree solution, rather than unfree water as such. In the latter case the displaced solution should have the same concentration as the soil solution.

SILTY CLAY LOAM SOILS.

The mechanical difficulties involved in displacing the solutions; the prolonged period sometimes requisite for displacement, involving the possibility of biological changes; the numerous duplications necessary to permit of the elimination of solutions from tubes giving inconsistent or irregular results; all contribute toward making the study of soils containing substantial quantities of colloidal material both tedious and uncertain. Our preliminary results with silty clay loams point to the desirability of a more complete study of a larger number of soils of this type than is at present possible. The data in hand, however, have obvious implications which justify their presentation in spite of their limited amount.

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Table III B. *Concentrations of Solutions displaced from Silty Clay Loams*.*

Soil	Soil 1 C		Soil 5			
	22.5 % moisture		18.0 % moisture		9.0 % moisture	
	Δ (°C.)	Specific res.	Δ (°C.)	Specific res.	Δ (°C.)	Specific res.
		(ohms)		(ohms)		(ohms)
	·190	—	·144	—	N.D.	—
1st 5 c.c	·183	(150)† 161	·041	(338)† 382	Lost	159
2nd "	—	173	·020	498	—	162
3rd "	—	185	—	507	—	166
4th "	—	175	—	436	—	164
5th "	—	177	—	411	—	167
6th "	—	167	—	384	·150	168
7th "	—	161	—	379	—	170
8th "	—	161	—	360	—	169
9th "	—	157	—	351	—	169
10th "	—	155	—	331	—	172
11th "	—	157	·060	340	—	172
12th "	—	158	·060	360	·150	173
Average	*—	166	—	395	—	168

* From Soil 1 C—six portions obtained the first day; portions 7, 8 and 9 the second day; portions 10, 11 and 12, the third day.

From Soil 5 (18 % moisture)—nine portions obtained the first day; portions 10, 11 and 12 the second day.

From Soil 5 (9 % moisture)—all portions obtained the first day.

† Solution obtained from a separate tube of soil without the aid of displacing water (see text).

We have already referred to the tendency toward lack of consistency between displaced solutions and between series of solutions displaced from different tubes of a silty clay soil (see p. 271). The specific resistances of solutions displaced from Soil 5 at 9 per cent. moisture agree, however, fairly closely, and the ratio of their average (168) to the specific resistance of the portion displaced without addition of water from the soil at 18 per cent. moisture (338) is in direct relation to the moisture contents of the soil. It is true that only one of the four tubes displaced by water from the soil at 18 per cent. moisture (D Table 2) gave solutions comparable to that obtained without the aid of displacing water but in this instance the agreement is very close. It was not possible to determine the freezing-point depression on this soil at 9 per cent. moisture and the determination on the soil at 18 per cent. certainly does not agree with that of the solution displaced. On the other hand, the successive portions of solution from Soil 1 C at optimum moisture agree quite closely in specific resistances with each other, with the solution displaced without water, and the freezing-point depression approximates very closely that of the soil itself.

It appears probable that the properties of Soil 5 require the presence of more than 18 per cent. of water in the soil for its freezing-point depression to approximate that of the displaced solution. Without stressing the importance of such meagre data, it seems probable that the lack of agreement of freezing-point depressions of soil and displaced solution, and the irregularities observed in solutions displaced have a common origin in the large amounts of colloidal material in such a soil, as compared with those of sands.

EQUILIBRIUM STUDY OF SOIL AND DISPLACED SOLUTION.

In a previous paper from this laboratory (7), it was suggested that if it were possible to obtain the true soil solution, it should, when passed through another portion of the same soil, remain unaltered in composition. Such a test is applicable in the case of displaced solution and has been carried out with interesting results. The procedure consisted in displacing six tubes (A to E) of Soil 8, according to our usual method. Specific resistances of solutions from all tubes were just as consistent as those reported heretofore for this soil, but had a slightly different value, owing to the fact that the moisture content (15.4 per cent.) was slightly higher and displacement was carried out some months later. The data from tubes E and F, Table IV A, indicate the range of concentration.

The amount of displacing water used was 310 c.c., i.e. equivalent to the moisture in the soil (15.4 per cent. of 2 kilos) and 31-10 c.c. portions were collected. The solutions from the first 21-10 c.c. portions of tubes A, B, C, D, were composited and used as displacing liquid on two additional tubes of the same soil (G and H). After collecting 31-10 c.c. portions from these tubes, they were again displaced, 310 c.c. of distilled water (G' and H') being used as the displacing agent.

It will be observed that from tubes E and F 25-10 c.c. portions, equivalent to 81 per cent. of the moisture of the soil, were obtained without change of concentration or evidence of dilution. From tubes G and H, the solution remains unaltered in the entire series of displaced solutions, pointing to the fact that the solution used in displacement probably had the same concentration as the solution with which it came in contact in the soil. Finally, in G' and H', when displaced by water, evidence of dilution begins to appear as in E and F, in the 26th portion. The extraordinary concordance of these results is shown in Fig. 1, where the graphs representing dilution in each case are superimposable.

The chemical analyses of solutions are confined to the first 21-10 c.c. portions, because these embrace the range used in making the composite

solution collected from tubes A, B, C, D, and used in displacing G and H. In view of the uniformity of the specific resistances of portions 22-25, inclusive, these would doubtless have given similar analytical results. The analytical figures in Table IV A are especially cogent, since they represent two to four times as much solution as that used in previous work and gave titrations and precipitates of sufficient amount to eliminate largely experimental error. It hardly seems necessary to point out that the concordance of analytical results with specific resistances makes it quite certain that the displaced solutions have not been diluted in the range where determinations were made.

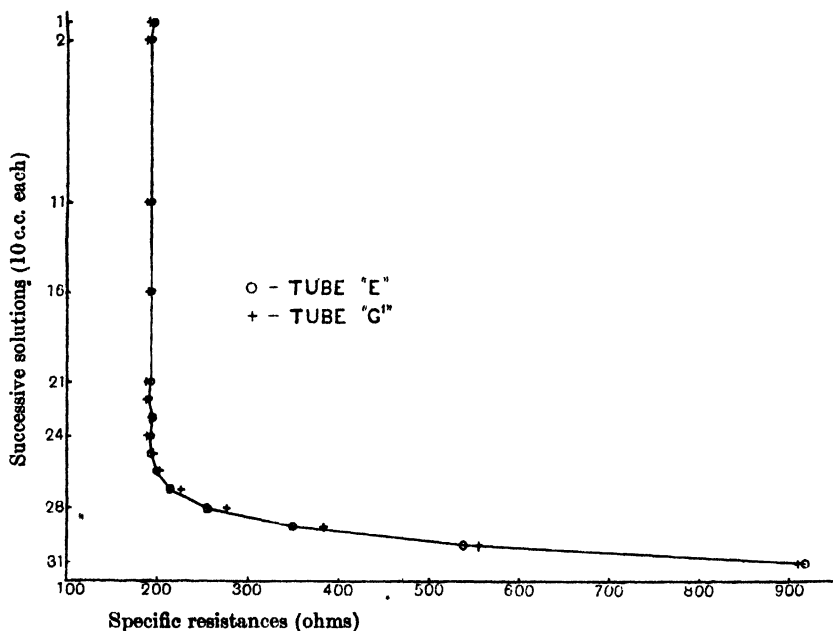


Fig. 1. Dilution by displacing liquid (see Table IV A).

A similar experiment to that just reported was made with a silty clay loam soil. The conditions of this experiment are indicated in the following table. It should be noted, however, that the follow-up treatment with distilled water was not carried out. This experiment was performed prior to the one reported in Table IV A and it had not then occurred to us to introduce the modification of the later experiment.

In studying these results, it should be noted that the rate of displacement was very much slower than in the sandy soil and that the recovery of the entire 12.5 c.c. portions took a number of days, whereas

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all displacements from the sandy soil reported above required only a few hours.

Table IV B. *Equilibrium Study of Displaced Solutions from a Silty Clay Loam Soil (1 C)*.*

Two kilos of Soils (22.5 % moisture) in each of Two Tubes.

	Tube B					Tube O				
	Displaced by distilled water (120 c.c.)					Displaced by a solution previously obtained by water displacement from a mass of the same soil (60 c.c.)				
	Solutcs as P.P.M. of solution					Solutcs as P.P.M. of solution				
	Spec. res. (ohms)	Ca	Mg	K	NO ₃	Spec. res. (ohms)	Ca	Mg	K	NO ₃
1st 5 c.c.	161	—	—	—	2753	159	—	—	—	2778
2nd "	173	—	—	—	—	154	—	—	—	—
3rd "	185	600	586	—	—	162	740	572	—	—
4th "	175	—	—	77	—	156	—	—	122	—
5th "	177	—	—		—	Lost	—	—	97	—
6th "	167	—	—	—	—	152	—	—		—
7th "	161	—	—	—	—	157	—	—	—	—
8th "	161	—	—	80	—	158	—	—	—	2976
9th "	157	—	—		—	134	—	—	—	—
10th "	155	720	614	—	—	112	—	—	—	—
11th "	157	—	—	—	—	126	—	—	—	—
12th "	158	—	—	—	2703	97	—	—	—	—

* From tube B—six portions obtained the first day; portions 7, 8 and 9 the second day; portions 10, 11 and 12 the third day.

From tube O—eight portions obtained the first day; portions 9 and 10 the second day; portion 11 the third day; portion 12 the fourth day.

Fortunately, the first eight portions from the tube O were obtained the first day, and these all show concentrations equivalent to those where water was the displacing agent. The anomalous and progressive increase in concentration in solutions 9 to 12 is not explainable in the light of the present data, and we can only suggest the possibility of biological changes having occurred and leave the question open for subsequent study. The experiment has a minor value, however, as showing again that even with fairly heavy soils, it was possible to obtain a small proportion (40 c.c. out of a possible 450 c.c. in this case) of solution which had not been affected by the character of the displacing agent.

COMPOSITION OF DISPLACED SOLUTIONS.

If the successive portions of displaced solutions of constant composition, as measured by their specific resistances, represent the true soil solution, they should contain equal quantities of all inorganic constituents. A test of this, therefore, required analysis of the individual

Table V A. *Analyses of Successive Portions of Displaced Solutions**.
(Solutes expressed as P.P.M. of Solution.)

Tube	SANDY LOAM													
	Soil 8 Bin. 14.8 % moisture							Soil 8 Bin. 7.3 % moisture						
	Spec. res. (ohms) A	Ca A	Mg A	K C	NO ₃ B	Cl D	PO ₄ ABCD	Spec. res. (ohms) A	Ca A	Mg A	K C	NO ₃ B	Cl D	PO ₄ ABCD
1st 5 c.c.	201	640	202	142	2580	(380)†	—	103	1280	278	250	5356	720	—
2nd "	206	640	216	152	2430	340	—	104	1340	284	228	5183	720	—
3rd "	202	—	—	—	—	360	—	103	—	—	—	—	—	10.9
4th "	206	—	—	—	—	—	7.9	102	—	—	—	—	—	—
5th "	206	—	—	—	—	—	—	103	—	—	—	—	—	—
6th "	204	—	—	—	—	—	—	103	—	—	—	—	—	—
7th "	206	640	192	142	2332	320	—	103	1360	278	244	4885	680	—
8th "	206	—	—	—	—	—	—	108	—	—	—	—	—	—
9th "	206	—	—	—	—	—	9.1	104	—	—	—	—	—	11.1
10th "	204	—	—	—	—	—	—	104	—	—	—	—	—	—
11th "	206	—	—	—	—	—	—	106	—	—	—	—	—	—
12th "	206	640	206	158	2480	320	—	107	1260	226	276	4860	680	—
Average	205	640	204	150	2460	335	8.5	104	1310	267	250	5071	700	11.0

* See Table II for specific resistances of tubes B, C, D.

† Solution obtained from a separate tube of soil without the aid of displacing water.

Table V B. *Analyses of Successive Portions of Displaced Solutions.*
(Solutes expressed as P.P.M. of Solution.)

SANDY LOAM

Tube	Soil 9 Bin. 14.3 % moisture										Soil 9 Bin. 7.5 % moisture									
	Spec. res. (ohms) A	Ca A	Mg A	K C	NO ₃ B	Cl D	PO ₄ ABCD	Spec. res. (ohms) A	Ca A	Mg A	K C	NO ₃ B	Cl D	PO ₄ ABCD						
1st 5 c.c.	276	480	158	85*	1165	(600)† 800	—	145	940	192	133*	1910	1380	—						
2nd "	292	460	148	85*	1042	(580)† 700	—	145	960	192	133*	1884	1340	—						
3rd "	289	—	—	—	—	—	1.1	145	—	—	—	—	—	1.1						
4th "	287	—	—	—	—		144	—	—	—	—	—		—						
5th "	289	—	—	—	—		143	—	—	—	—	—		—						
6th "	289	—	—	—	—	—	—	143	—	—	—	—	—	—						
7th "	289	480	120	85*	1116	640	—	145	1000	202	129*	1810	1260	—						
8th "	287	—	—	—	—	—	—	145	—	—	—	—	—	—						
9th "	292	—	—	—	—	—	1.1	147	—	—	—	—	—	1.3						
10th "	287	—	—	—	—		149	—	—	—	—	—		—						
11th "	283	—	—	—	—		151	—	—	—	—	—		—						
12th "	289	480	124	85*	1042	620	—	154	1040	182	129*	1736	1160	—						
Average	287	475	140	85	1090	690	1.1	146	985	190	130	1835	1280	1.2						

* 1st and 2nd, and 7th and 12th portions represent composites.

† Solution obtained from a separate tube of soil without the aid of displacing water.

Table V c. *Analyses of Successive Portions of Displaced Solutions.*

(Solute expressed as P.P.M. of Solution.)

SANDY LOAM

Tube	Soil 11 Bin. 16.6 % moisture										Soil 11 Bin. 8 % moisture					
	Spec. res. (ohms)	Ca	Mg	K	NO ₃	Cl	PO ₄	Spec. res. (ohms)	Ca	Mg	K	NO ₃	Cl	PO ₄		
1st 5 c.c.	285	A	—	—	1460	A	B	122	—	—	—	2286	A	N.D.†		
2nd "	289	420	139	—	—	460	—	138	720	288	—	2254	1080	—		
3rd "	292	—	—	122	—	—	12.5*	147	—	—	160	2104	—	—		
4th "	295	—	—	—	1320	460	—	152	—	—	—	2352	940	—		
5th "	296	420	182	—	—	—	12.5*	153	820	292	—	2222	—	—		
6th "	294	—	—	142	—	—	—	155	—	—	177	2192	—	—		
7th "	292	—	—	—	—	460	—	N.D.	—	—	—	—	880	—		
8th "	289	420	182	—	1460	—	—	"	800	274	—	—	—	—		
9th "	289	—	—	145	—	—	12.5*	"	—	—	160	—	—	—		
10th "	283	—	—	—	—	460	—	"	—	—	—	—	860	—		
11th "	283	420	213	—	—	—	—	"	820	284	—	—	—	—		
12th "	285	—	—	154	1320	—	—	"	—	—	177	—	—	—		
13th "	—	—	—	—	—	—	—	"	—	—	—	—	—	—		
14th "	—	—	—	—	—	—	—	"	780	288	—	—	860	—		
15th "	—	—	—	—	—	—	—	"	—	—	160	—	—	—		
Average	289	420	179	140	1390	460	12.5	145	790	285	165	2235	925	—		

* One composite sample.

† Insufficient solution.

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portions rather than of a composite. In most instances, the concentrations of the various ions are likely to be so small that a 5 c.c. portion if divided for all of the usual determinations would afford too little solution for precise determination. The expedient was adopted, therefore, of making all determinations of a given element from the solutions derived from displacement of a given tube of soil.

Table V D. *Analyses of Successive Portions of Displaced Solution.*
(Solutes expressed as P.P.M. of Solution.)

SILTY CLAY LOAM

Tube	Soil 1 C. 22.5 % moisture					
	Spec. res. (ohms)	Ca	Mg	K	NO ₃	PO ₄
	B	B	B	B	B	A to L*
1st 5 c.c.	161	—	—	—	2753	—
2nd "	173	—	—	—	—	—
3rd "	185	600	586	—	—	—
4th "	175	—	}	—	—	—
5th "	177	—		77	—	—
6th "	167	—	—	—	—	5.1
7th "	161	—	—	—	—	6.0
8th "	161	—	}	—	—	—
9th "	157	—		80	—	—
10th "	155	720	614	—	—	—
11th "	157	—	—	—	—	—
12th "	158	—	—	—	2703	—
Average	166	660	600	80	2726	5.6

* Duplicate determinations made on a solution from other tubes (A to L) of same spec. res. as tube B.

In considering these data it must be borne in mind that the amount of solution available was small (5 c.c. for most determinations) and some allowance must be made for the experimental error involved. The following information is submitted so that the reader may draw his own conclusions as to the significance of the various figures reported. Potassium was determined by weighing the precipitate of K_2PtCl_6 . Nitrates were determined by the Devarda method and titration with $n/50$ acid; calcium by precipitation as calcium oxalate and titration of the dissolved precipitate in the presence of sulphuric acid with $n/20$ $KMnO_4$; magnesium by precipitation as ammonium magnesium phosphate, precipitate dissolved in excess of $n/50$ H_2SO_4 and excess titrated with $n/50$ $NaOH$; chlorine by titration with $AgNO_3$ solution in which 1 c.c. = 1 mg. Cl ; phosphate by precipitation as ammonium phosphomolybdate, precipitate dissolved in excess of $NaOH$ (1 c.c. = 0.1 mg. PO_4), the excess titrated with HNO_3 of the same strength.

Table V E. *Analyses of Successive Portions of Displaced Solutions**.

(Solutes expressed as P.P.M. of Solution.)

SILTY CLAY LOAM

Tube	Soil 5 Bin. 18 % moisture							Soil 5 Bin. 9 % moisture						
	Spec. res. (ohms)	Ca	Mg	K	NO ₃	Cl	PO ₄	Spec. res. (ohms)	Ca	Mg	K	NO ₃	Cl	PO ₄
1st 5 c.c.	382	420	206	79†	2083	D	ACD	B	A	336	119†	3050	B	ABC
2nd "	498	340	140	79†	2406	—	—	159	860	302	119†	2902	—	—
3rd "	507	—	—	—	—	—	—	162	840	—	—	—	—	—
4th "	436	—	—	—	—	—	—	166	—	—	—	—	—	—
5th "	411	—	—	—	—	—	—	164	—	—	—	—	—	6.9
6th "	384	—	—	—	—	140	—	167	—	—	—	—	320	—
7th "	379	440	158	95†	2182	—	—	168	840	288	133†	2505	—	—
8th "	360	—	—	—	—	—	—	170	—	—	—	—	—	—
9th "	351	—	—	—	—	—	—	169	—	—	—	—	—	—
10th "	331	—	—	—	—	—	7.3	169	—	—	—	—	—	—
11th "	340	—	—	—	2034	—	—	172	—	—	—	2654	—	6.7
12th "	360	440	172	95†	—	160	—	173	840	356	133†	—	320	—
Average	395	410	165	85	2175	150	5.8	168	845	320	125	2778	320	6.8

* See Table II for specific resistances of tubes B, C, D (at 18 % moisture); A, C' (at 9 % moisture).

† 1st and 2nd and 7th and 12th portions represent composites

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Referring to our tables it will be observed that the general magnitudes of the solutes in successive solutions show a good agreement. There is occasional evidence of a progressive increase or decrease of various constituents, but the variation is not usually great. With the exception of a few doubtful cases the results, in our view, indicate that the successive solutions are of uniform or practically uniform concentration within the range collected and thus tend to confirm the same conclusion drawn from the corresponding determinations of specific resistance. In conformity with this opinion and to simplify discussion, the average composition of each series of solutions is re-stated in the following tabulation together with data obtained by extraction of the soils with varied quantities of water. It should be noted that these latter were always made from soils at the higher moisture percentage (optimum) and are computed in terms of the corresponding amount of water. Comparisons should therefore be made between water extracts and solutions displaced at the higher moisture content, the nature of the displaced solutions at the lower moisture content being inferred from comparisons of the two displaced solutions.

Examination of Table VI reveals so many interesting relations that it is difficult to avoid advancing speculative suggestions unwarranted by the amount of data at hand or the accuracy of determinations on limited volumes of solution. This latter objection can be overcome in future work by collecting more and larger increments of solution as our experience has subsequently shown that larger yields of solution undiluted by displacing liquid are readily obtained, at least from the lighter soils. (See tubes E and F, Table IV A.)

The displaced solutions reveal numerous instances which conform fairly closely to an inverse proportion between concentration of solutes in the pairs of displaced solutions and the initial moisture contents of the respective soils from which they were obtained. Calcium and chloride show this relation in all soils displaced at more than one moisture content, magnesium shows it in Soil 5, nitrate shows it clearly in Soil 8 and less definitely so in Soils 9 and 11. The implications of this relation are, of course, the same as those of the similar one shown for total concentration of these same solutions as measured by freezing-point depressions and specific resistances. It will be noted, however, that certain constituents, such as potassium, do not show the inverse relation to total moisture content, which, if the displaced solutions afford a measure of concentration of the true soil solution, would imply that potassium is thrown out of solution in these soils by diminishing the amount of soil moisture.

Table VI. *Solutes in Displaced Solutions and Water Extracts.*

Displaced solutions in parts per million as obtained. Extracted solutions computed in terms of parts per million of the moisture (optimum) in the soil at time of extraction.

Soil Number	Moisture %	Description of solutions	Composition of solutions					
			Calcium (Ca)	Magnesium (Mg)	Potassium (K) (Parts per million)	Nitrate (NO ₃)	Chlorine (Cl)	Phosphate (PO ₄)
8	7.3	Displaced	1310	265	250	5070	700	11.0*
	14.8	"	640	204	150	2460	335	8.5*
	"	Extracted (1-1)	592	184	322	2160	350	69.0
	"	" (1-2.5)	592	167	351	2165	365	92.0
9	"	" (1-5)	627	178	408	2105	340	115.0
	7.5	Displaced	985	190	130	1835	1280	1.2*
	14.3	"	475	140	85	1090	690	1.1*
	"	Extracted (1-1)	413	84	108	964	560	9.6
11	"	" (1-2.5)	371	96	132	739	567	22.0
	"	" (1-5)	Lost	Lost	228	812	611	40.0
	8.0	Displaced	790	285	165	2235	925	N.D.†
	13.6	"	560	245	180	N.D.	690	9.8*
1 C	16.6	"	420	179	140	1390	460	12.5
	"	Extracted (1-1)	334	112	291	1477	422	95.0
	"	" (1-2.5)	268	102	342	1237	446	170.0
	"	" (1-5)	250	102	454	1191	435	237.0
5	22.5	Displaced	660	600	80	2726	—	5.6*
	"	Extracted (1-1)	500	345	135	2639	—	1.0
	"	" (1-2.5)	530	386	165	2702	—	24.0
	"	" (1-5)	525	373	200	3143	—	24.0
5	9.0	Displaced	845	320	125	2778	320	6.8*
	18.0	"	410	165	85	2175	150	5.8*
	"	Extracted (1-1)	432	159	159	1609	183	46.0
	"	" (1-2.5)	582	223	235*	1562	185	82.0
"	" (1-5)	546	218	319	1149	149	96.0	

* Soil 8. Phosphate, 10.9-11.1 and 7.9-9.1. Soil 9. Phosphate, 1.1-1.3 and 1.1-1.1. Soil 11. Phosphate, 9.6-10.0.

Soil 1 C. Phosphate, 5.1-6.0. Soil 5. Phosphate, 6.7-6.9 and 4.2-7.3.

† Insufficient solution.

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It may well be asked, why it is, if some constituents are withdrawn from solution, that the total concentration of electrolytes should show the inverse relation to moisture content. The answer would appear to lie in the large amounts of the other constituents which are not rendered insoluble by reducing the moisture content in the range here covered.

The behaviour of phosphate is in interesting contrast to that of those constituents showing the inverse relation to moisture content. The absolute amounts of this constituent in the displaced solutions are so small and the volume of solution so limited (see Table V for exact amounts), that a considerable experimental error must be assumed. In our view, however, the phosphate concentrations of the pairs of displaced solutions may be regarded as identical and as constituting a saturated solution in each instance. If the soil solution is saturated with reference to phosphate, it is equally clear that none of the other constituents partake of this condition in the displaced solutions at the higher moisture content, for otherwise the pairs of displaced solutions should have equal concentrations of such constituents.

Where the inverse relation appears for any constituent, it is evident that the solution displaced at the higher moisture content is not saturated and that the concentration of the solution displaced at the lower moisture has not passed the point where dissolved material is precipitated out. The condition of those constituents which, like potassium, have a greater concentration in solutions displaced from soils at the lower moisture content, but which do not increase in concentration in proportion to the diminished amount of moisture in the soil, is not easy to explain. The total amount of solutes of all kinds, including those ions not determined, probably does not exceed 10,000 P.P.M. or a 1 per cent. solution in any of our soils. This represents only a small fraction of the degree of solubility of chlorides, nitrates and carbonates of potassium in pure solutions. Moreover, the chemical properties of potassium in pure solutions are such that in the absence of evidence to the contrary, we should expect the soluble potassium of soils to fluctuate somewhat in accord with those anions which are present in relatively high concentrations. This, however, it fails to do in marked contrast with the behaviour of the di-valent element calcium, the salts of which generally are less soluble and which should be precipitated before those of potassium. Even if, as is doubtless the case, the undetermined bicarbonate is a factor in preventing the precipitation of calcium in the solution displaced from soils at the lower moisture contents, this anion should not depress the solubility of potassium. Apparently, then, the behaviour of potassium cannot be accounted for

by purely chemical relationships unless it be assumed that certain potassium silicate or organic complexes are more readily formed, or more insoluble than the analogous calcium compounds, which is not likely. The alternative would seem to be that potassium ion in soils at low moisture contents is peculiarly susceptible to colloidal adsorption (13). The displacement method appears to afford a means of measuring this effect with precision, and thus offers the hope, in more complete and specialised studies, of determining its cause.

WATER EXTRACTS AND DISPLACED SOLUTIONS.

Displaced solutions of constant composition in successive increments may or may not constitute the soil solution. If, however, they are not entitled on present evidence to be so regarded, they at least give the kind of data to be expected from water extractions if we could use proportions of water and soil comparable to those involved in the field when plants are actively growing. As such, they eliminate some of the more important objections which have been raised to water extractions of the ordinary type. On the other hand and to the extent to which displaced solutions are found to confirm results by water extraction, the former may be used to corroborate and extend the conclusions which have been drawn from the latter. Since it is at once obvious from the tabulated data that there is a general agreement between the results by the two methods, it would appear timely to restate the conclusions, largely based on water extractions, which have been put forward from time to time from this laboratory and to discuss their validity in the light of the present results.

These views may be briefly stated as follows:

1. The soil solution at moisture contents favourable to plant growth does not have a high concentration and is not saturated in the ordinary sense of the term except with reference to phosphate and possibly silicate ion and organic complexes which have not been thoroughly studied.

2. The total concentration of the soil solution fluctuates at least in proportion to the moisture content of the soil.

3. Freezing-point depressions(2), dilatometer measurements(1), and vapour pressure effects(8) may be accounted for on the theory that the concentration of the soil solution is enhanced by the elimination as a solvent of a part of the soil's water. The correlation of water extractions with freezing-point depressions on cropped soils at the height of the growing season, when low concentrations of solutes should increase the colloidal condition in soils, together with low absolute values for freezing-point depressions at that time, suggests that the relatively great increase

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of such values with diminishing soil moisture content may not be exclusively due to an enhanced concentration caused by the partial withdrawal of water as a solvent. If the values of the observed physical constants are due in part to some other effect than enhanced concentration of the soil solution, it is clear that the concentrations estimated from water extractions computed to the total moisture of the soil approach more nearly the true value than has been hitherto assumed (6).

4. The growth of plants materially reduces the concentration of the soil solution for those constituents other than phosphate which are removed by the plant in substantial quantities.

5. A considerable time, usually a number of months, is necessary for the soil solution subjected to the growth of a crop to regain its approximate previous concentration.

6. Biological activities affect the concentration of the soil solution directly and indirectly.

Three distinct types of behaviour have been shown in the previous discussion of solutions displaced at different moisture contents.

(a) The concentrations of a given solute are inversely proportional to moisture contents of the soil; illustrated in our soils by calcium, nitrate and chloride.

For the constituents which fall in this class, the water extractions and particularly the (1-1) extraction give figures of the same order of magnitude and frequently agree very closely with those obtained by displacement of soil initially at the same moisture (optimum) content. Nitrate in Soil 5 may, perhaps, be regarded as an exception. These results, with the exception noted, are consistent with the idea that those ions which tend to form comparatively soluble salts, should be accounted for by water extraction. This obviously applies to nitrate and chloride. Moreover, an ion like calcium, which tends to form salts of low solubility, should be dissolved by water, if in equilibrium with oppositely charged ions capable of forming highly soluble salts. The anomalous behaviour of potassium in this respect has already been considered (see p. 288) and must be explained on other grounds.

(b) The concentrations of the solutes in solutions displaced from a given soil at different moisture contents are equal; illustrated by phosphate.

The conclusion is equally deducible, from the behaviour of the displaced solutions and the water extractions with varied quantities of water, that phosphate tends to form a saturated solution in the soil's moisture. The figures show, however, that the concentration of solutions

from different soils may vary considerably—probably in accord with the particular physico-chemical system involved. The phosphate concentrations computed from extractions with an excess of water indicate values which are higher than those obtained from the displaced solution by an amount proportional to the masses of water involved, i.e. for the (1-1) extract.

$$\frac{100 + \text{percentage of moisture (optimum)}}{\text{Percentage of moisture (optimum)}}$$

This would appear to mean that water extractions however computed, whether on a basis of water-free soil, upon the amount of water in the soil or in terms of concentration of the extract itself, have a certain validity for comparisons of the relative content of soluble phosphate in different soils. For estimation of the phosphate concentrations of the soil solution, or comparison of phosphate concentrations with those of other ions, the estimates from water extractions must be computed with reference to the relative amount of water in the soil and that used in the extraction as just indicated.

(c) The concentrations of the given solute in the solutions displaced from soils at low moisture are higher than those displaced from soils at high moisture, but not in proportion to moisture contents; illustrated by potassium.

The relation between concentrations of potassium in the soils displaced at the higher moisture (optimum) and those computed from the corresponding water extractions tend to confirm the opinion, based upon water extractions alone, that these latter yield results which are several fold too high for this constituent. Neither the behaviour of the displaced solutions, nor that of the water extractions, suggests that the soil moisture is saturated with reference to potassium in soils at the higher moisture content, so that a correction based upon that condition is not applicable. Water extractions cannot, therefore, be utilised to compute the potassium concentration of the soil's moisture with any degree of precision.

In the preceding discussion, we have attempted to classify the various soil constituents on a basis of typical behaviour. Notable exceptions to a characteristic behaviour are observable in the case of magnesium, which in one soil behaves like calcium and in others partakes to some extent of the behaviour typical of potassium in the displaced solutions, but shows decreased concentrations by water extraction. Nitrate shows several instances where smaller concentrations are indicated by water extraction than by the displaced solution. These anomalies we shall

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not attempt to explain in the light of the present data, and will content ourselves with the suggestion that colloidal adsorption could produce some of the effects to which reference has been made.

It would appear, however, that the displacement method has much to recommend it in the study of this phenomenon, provided the data are sufficiently numerous, and more complete analyses of the displaced solutions are procured. Such work is now going forward in this laboratory.

MECHANISM OF THE DISPLACEMENT PROCESS.

The condition of the moisture of tightly compacted soils in a tube is certainly very different from that in the field. We early observed in all soils at their higher initial moisture contents, that the volume of displacing water entering the soil mass was approximately equal to the volume of solution displaced, being in some cases slightly greater and in others slightly less, but indicating that there was no substantial change in percentage of water in the soil during displacement. It is evident that this condition might come about because the soil is saturated, in the sense that all the pore spaces are filled with water to the exclusion of air, or in the more restricted sense that the surface tension of the soil particles is inadequate to retain the water entering from above, except as the latter replaces an equal volume of displaced solution. Careful measurements of soil and water volumes indicate that the first kind of saturation represents the condition existing in compacted soils. The data from a silty clay loam soil (5) at 18.4 per cent. moisture, were as follows:

Water on top of soil mass at commencement	...	...	...	...	...	400	c.c.
Water on top of soil mass at conclusion, averages of four tubes (355, 350, 350, 350)	...	...	...	...	...	351	"
Water entering soil during displacement	...	...	...	...	...	49	"
Solution collected (12-5 c.c. portions)	...	...	...	...	...	60	"
					Lost from soil	11	"
Diameter of tube, 7.3 cm.							
Cross section of tube, 41.85 sq. cm.							
Height of soil column, averages of four tubes (23.3, 23.1, 22.6, 22.7 cm.) 22.9 cm.							
Superficial volume of moist soil	...	...	...	...	...	958.4	"
Moist soil	2000	g.					
Water in soil	368	g. (18.4 % of 2 kilos)					
Water-free soil	1632	g.					
Assuming average sp. gr. of soil particles at 2.7							
Volume of water-free soil (computed)	...	...	...	...	...	604.4	"
Volume of water and air spaces in soil	...	...	...	...	...	354.0	"
Water in soil, 368 c.c.—loss of water during displacement, 11 c.c.	...	...	...	...	...	357.0	"
					Air space	- 3.0	"

Turning to soils displaced at the lower initial moisture content, the volume of displacing water entering the soil mass was greater than that displaced by an amount just about equivalent to that required to build up the moisture content to its optimum. Measurements from such soils show that all or most of the space initially occupied by air had been filled with water during the process of displacement. The following results from Soil 5 at 9.2 per cent. moisture are presented in this connection:

Water on top of soil mass at commencement	...	...	...	...	...	400	c.c.
Water on top of soil mass at conclusion, average of three tubes (100, 100, 90 c.c.)	...	...	...	...	...	97	„
Water entering soil during displacement	...	...	...	...	...	303	„
Solution collected (12-5 c.c. portions plus drip)	...	...	...	...	...	77	„
Gained by soil						226	„

Diameter of tube, 7.3 cm.

Cross section of tube, 41.85 sq. cm.

Height of soil column, average of three tubes (26.6, 26.5, 26.9 cm.) 26.7 cm.

Superficial volume of moist soil 1117 „

Moist soil 2000 g.

Water in soil 184 g. (9.2 % of 2 kilos)

Water-free soil 1816 g.

Assuming average sp. gr. of soil particles 2.7

Volume of water-free soil 673 „

Volume of water and air spaces in soil 444 „

Water in soil (184) plus gain in water (226) 410 „

Air space 34 „

Final percentage of water in soil $\frac{184 + 226}{2000 + 226} = 18.4 \%$.

The apparent air space (34 c.c.) would be smaller if the assumed sp. gr. used in the calculations is too high, which is probably the case. In any event, it is evident that, after any considerable volume of displaced solution (60 c.c. out of a possible 184 c.c.) has been recovered, the soil is practically saturated. Another series of similar measurements and computations on soils at low moisture content was carried out in a tube from which displacement was stopped as soon as solution began to appear. The result was an apparent air space in the soil core of 11 c.c., indicating that under our method of packing, all of the soil space is filled with water before any solution issues from the apparatus. It would appear, then, that displacement under these conditions is a piston-like effect resulting in an actual translocation of successive layers of liquid, rather than an overcoming of surface tension, due to thickening of the soil film in a restricted sense.

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SUMMARY.

1. The use of a positive air pressure on closely packed soils decreases the time of recovery and increases the yield of solution obtained by water displacement.
2. Equipment and technique for the recovery of displaced solutions is described.
3. Data from three sandy loams and two silty clay loams are reported.
4. Successive displaced solutions of equal electrical conductivity were obtained from each soil. The concentration thus measured was in each case the same as that of the liquid obtained without the use of displacing water.
5. Concentrations of individual ions in successive portions of displaced solution are uniform in soils at optimum and this also appears to be true at half optimum.
6. There is an inverse proportion between total moisture content of soil and concentration of displaced solution as indicated by measurements of specific resistance.
7. When the solution displaced by water from a given mass of soil was used as displacing agent on another portion of the same soil, the newly displaced solution had the same concentration of electrolytes as the displacing solution. The opinion is expressed that this result indicates that the displaced solution has the same concentration as the solution with which it came in contact in the soil.
8. Typical differences in behaviour of the various solutes in displaced solutions are discussed.
9. The significance and limitations of water extractions of soils are discussed in the light of the results from displaced solutions.
10. Evidence is presented which tends to show that compacted soils tend to become completely saturated during displacement and that the mechanism of displacement consists in an actual translocation of successive layers of liquid.

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THE VOLUME-CHANGES ASSOCIATED WITH VARIATIONS OF WATER CONTENT IN SOIL.

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(With Seven Text-figures.)

THE phenomena of shrinking and swelling which take place in most soils as the water content decreases or increases have attracted very general observation. Their effects may extend far beyond the range of purely agricultural interests, as for example, during the drought of 1921, when large numbers of houses suffered from shifting foundations, in consequence of the shrinkage of the subsoil which became dry to unusual depths. As a particular agricultural problem, shrinkage in soils comes to the fore in certain tropical clays, where the cracks which open in the soil in dry weather injure the root systems of the crop and depress yields. This problem led to the work of Auchinleck and his collaborators in the West Indies(1). But in general the great interest which attaches to the subject lies in the fact that the constant fluctuations in moisture to which most arable soils are subjected, by inducing corresponding shrinking or swelling, constitute a leading factor in the loosening of the structure of the soil and the formation of a good tilth. This paper presents the results of some shrinkage measurements undertaken during the course of a more extended investigation of some physical constants of soil. Since the method used is of great simplicity it is hoped that it will prove useful in the hands of other workers. In a paper which was found after the present work was well advanced Johansson(2) describes the essentials of the method. His use of it forms only a minor feature in his paper, and the results are not discussed in much detail.

Cameron and Gallagher(3) include some measurements of soil shrinkage among an extensive collection of physical data regarding soils. Like Wollny(4), to whose earlier work they refer, they endeavoured so to compact their soil samples as to resemble natural conditions. A soil column was made by packing under standardised conditions into a cylinder, then wetted, extracted from the mould, supported in an oblique

position and the linear shrinkage measured as drying took place. One or two of their curves do not seem very clear in the interpretation to be assigned to them. For example, they give the following figures for a black clay loam:

Moisture %	Volume decrease %	Moisture %	Volume decrease %
59.0	0.0	20.9	4.1
54.0	0.0	16.2	6.1
45.7	0.0	11.8	8.0
40.4	0.2	10.8	9.1
37.4	0.5	9.0	11.1
43.0	0.6	7.6	11.5
28.8	1.6	6.7	11.6
22.3	3.9		

It will be seen that one-third of the amount of water originally present was lost before the shrinkage became measurable. Now it is just over this first region that shrinkage is normally greatest. If the water has really been incorporated into the soil then its extraction by drying is at first accompanied by an equal decrease in volume. Two reasons may be advanced for this discrepancy, first that the structure of the soil column was so open that the water first lost was due to drainage and evaporation out of the larger crevices rather than to drying out of the capillary pores of the soil, and so had small effect on the total volume of the column. Secondly, the measurements were confined to the length of the column, and it may be that while the soil was very wet and plastic the shrinkage was mainly confined to a lateral direction, so passing unnoticed.

Tempany⁽⁵⁾ records some linear measurements of shrinkage based upon much improved experimental arrangements. In preparing his soils a process of kneading with water was adopted, which effectively destroyed any natural crumb structure that might be present in the original sample. This greatly adds to the consistency of the results and to the simplicity of their interpretation. For the purpose of comparing different soils Tempany takes the total shrinkage occurring between a moisture content defined as the point of maximum plasticity¹ and complete dryness. If difference in porosity of the dry soils be neglected, then the shrinkage so measured depends only on the moisture content at the

¹ Auchinleck (1) attempts a rigid definition of this term, based upon some work by Lake, as that condition in which a soil block of one inch square cross section is just able to be crushed in less than five seconds by a weight of 1 kg. transmitted by a lever through a halfpenny resting on the block. Tempany seems to have adopted this. In general it is one's experience that, where the soil can truly be said to show any plastic properties at all, it is easy for a worker to judge with fair accuracy a point when the soil is just *not* sticky, and shows its maximum plastic properties.

point of maximum plasticity, and hence a simple determination of moisture would suffice almost as well for making the comparison. In the work here presented it was intended to follow more closely the stages in shrinkage, i.e. the shape of the shrinkage curve, to see what light this might throw on the physical constitution of soil. Hence, in presenting the results the volume of the oven-dry soil has been chosen for the point of reference, as being capable of more rigid definition than the point of maximum plasticity or some other such point depending upon a personal judgment of physical properties.

The method adopted consists in measuring the volume changes which a small prism of soil undergoes during a slow drying-out process. The soil sample was first passed through a 100 mesh sieve, and then well worked up with water in a small incorporating machine. This is a hand-driven device for thoroughly mixing any plastic material by means of two revolving paddles working in opposition. It seems a fair assumption that such treatment thoroughly deflocculates the soil. Water was added gradually until the upper limit of plasticity was nearly reached, i.e. until the soil began to show signs of becoming sticky or fluid. A portion of the mass was then taken, given a further kneading by hand to work out any air bubbles it might contain, and moulded into a square prism with rounded edges and corners, roughly $6 \times 1 \times 1$ cm. in size. This was now ready for experiment, and had the highest moisture content that was compatible with safe handling. The drying-out process was suitably slowed down by the use of covers, so that the distribution of moisture in the prism would remain as uniform as possible. Some tests of this uniformity were made on a number of prisms at different stages by separate determinations of moisture on the inside and the outside layers, and in no case was the difference more than .2 per cent. Tests were also made on the possible influence of the cross-sectional shape of the prism on the shrinkage values, but no such effects were observed.

The volume measurements were made by displacement of mercury in a constant-volume bottle, shown in Fig. 1. This bottle has a ground-in perforated stopper like an ordinary specific gravity bottle, and the bottom is closed by a glass disc held by a washer and a brass screw-on cap, exactly like the end of a polarimeter tube. The removal of this disc allowed the insertion or withdrawal of the prism. The technique consists simply in weighing the mercury required to fill the bottle with and without the soil prism present, and calculating the displaced volume. Corrections are applied for temperature, as the bottle and mercury get warmed by unavoidable handling. The soil prism is weighed at the same

time that a reading of its volume is taken, so that the water content may be found from comparison with the final oven-dry weight. It may not be out of place to mention one or two small details as to the filling of the bottle with mercury. Firstly, the end of the prism which comes uppermost must be made wedge-shaped, so that, as the upthrust of the rising mercury forces the prism into the neck of the bottle, it does not block the entry of more mercury. Secondly, very careful manipulation is required to get rid of air bubbles which cling to the glass or soil surfaces. Particularly is this the case at the point where the prism touches the glass. The surface tension of the mercury tends to drag it away from this point and leave a space. If the soil prism is a dry one and contains air in its pores, then each time a bubble is detached from this point a fresh one will form, air being supplied from the interior of the prism until the air pressure in the soil is sufficiently lowered. The texture of a prism prepared as described is fine enough to prevent any mercury entering its pores, so that error does not arise from such a cause.

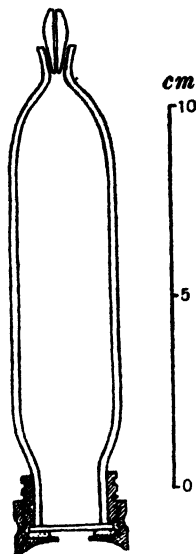


Fig. 1.

The diagram in Fig. 2 indicates the method of plotting the results. When the term "soil volume" is used it is understood to mean the total volume occupied by the soil framework, whether its interstices are filled by air or water or both. The soil volume is plotted against the volume of water present, all readings being so reduced as to refer to 1 c.c. of oven-dry soil. Special attention must be drawn to the use of this unit, as it is customary to think of moisture expressed in terms of unit weight of material, not unit volume. No doubt this convention has arisen from the much greater ease and accuracy with which a measurement of weight can be carried out than a measurement of volume, but there are many cases, like the present, where the volume unit is more logical. It is found that the curve obtained by plotting as indicated consists, to a first approximation, of two straight lines. The implications of this are best discussed if, for the moment, we suppose the process of drying to be strictly reversible, so that we start with an oven-dry prism and work backward along the shrinkage curve by successive increments of water. The first part *AB* of the curve *ABC*, Fig. 2, making a small angle θ with the axis, represents the stage where the pore space of the soil is partly filled with air and partly with water. The second part *BC'*

corresponds to the stage when, all the air having been displaced by water,^a each increment of water is accompanied by an equal increment of volume, and the curve takes an upward course at an angle of 45° . The length of BC will depend upon the capacity of the soil to imbibe water without becoming either sticky or fluid—that being the point at which readings have to cease. With a sandy soil BC is short or evanescent, since sand becomes fluid directly its pores are filled with water and the surface

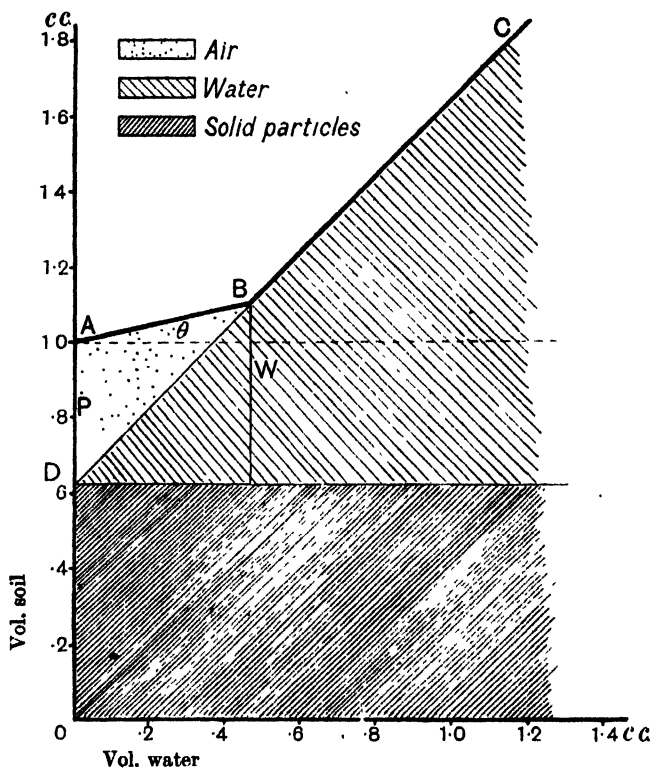


Fig. 2.

tension of liquid films between the particles ceases to hold them together; with a clay BC may extend up to twice the original volume or a little more; while with some measurements made on gelatine it extended to nine or ten times the original volume. If the soil has been properly worked up so as to exclude all air bubbles, it may be assumed that, over the range represented by BC , there are only water and solid particles present. Hence, if CB be produced to cut the axis at D , then OD will represent the volume occupied by the solid particles alone (since BC runs

Apparent s.g. = 2.037. $P = .246$. $1 - P = .754$. Real s.g. = 2.700.

A characteristic set of experimental figures for a clay separate is given in Table I. On plotting the curve from the data in the last two columns it is found to conform very closely to the two straight lines of Fig. 2. There is naturally a slight smoothing out at the point of inflexion, and the last part of the curve bends again just before reaching zero. There is always a little uncertainty about the last point or two, owing to small cracks appearing in the soil prism as a result of oven treatment. An improvement in future measurements would be to dry without heat over sulphuric acid. It will be noticed that at one point in the readings in Table I, marked by a star, there is a step backward up the curve. This was caused by leaving the clay prism in too moist an atmosphere, so that it took up water instead of losing it. That clay, already containing 34 per cent. of water, should take up moisture so readily indicates the great affinity this fraction of the soil has for water.

In Table II is given a list of the soils chosen for presentation in this paper, together with those results of their mechanical analyses which bear on the present issue, and the reference letters by which they are denoted on the diagrams.

Table II.

Soil	Fine sand	Silt	Fine silt		Clay	Loss on ignition
			I	II*		
A Clay separate ...	—	—	—	—	90.5	9.5
B Kaolin ...	—	—	—	11.7	52.8	12.4
C Clay (Sudan) ...	16.2	11.8	4.7	4.8	42.3	11.4
D Clay subsoil (Durham)	16.1	14.5	13.3	9.7	33.8	9.6
E Harpenden Common	17.8	32.0	9.0	8.3	25.2	10.5
F Loam (Rothamsted) ...	28.6	33.8	10.0	4.9	14.8	8.3
G Sandy (Norfolk) ...	60.5	12.3	5.1	3.3	5.3	8.3
H Peaty ...	—	—	—	—	—	27.0

* The clay fraction on the American system of mechanical analysis = fine silt II + clay of the above table.

The results of shrinkage measurements on the above soils are shown graphically in Figs. 3 and 4. The two groups have been made in order to obtain suitable scales for drawing. The measurements begin at the top point of the curve, as already described, and all the soils may be considered to be roughly in the same physical condition at the commencement. Hence, one might follow Tempany and take the total shrinkage for the purpose of comparing soils. But it seems equally important to pay attention to that portion of the shrinkage which is accounted for in the second and lower portion of the curve. This is seen to vary a good deal in amount, and can be defined with fair accuracy since the point of inflexion is usually sharp. It is proposed to call this the "residual"

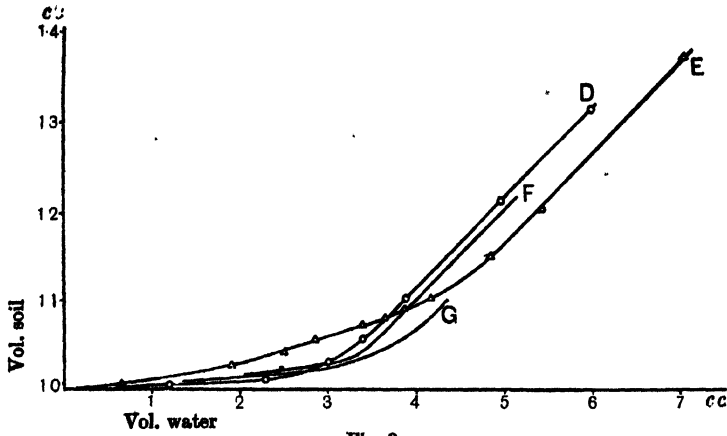


Fig. 3.

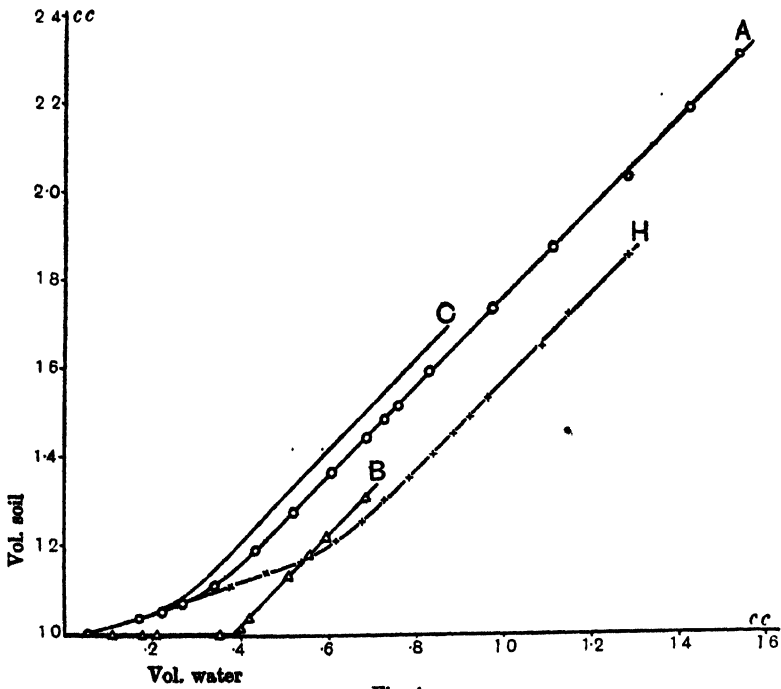


Fig. 4.

shrinkage. Referring to Fig. 2 it will be seen that the residual shrinkage is expressed by $(W - P)$ or $W \tan \theta$. Both total shrinkage and residual shrinkage will be expressed in terms of percentage of final (dry) volume. The total shrinkage varies from 130 per cent. in the case of pure clay down to about 9 per cent. in a sandy soil. In contrast with this the residual shrinkage is zero in the case of kaolin clay, and is greatest for a peaty soil at 18 per cent. (see curves *B* and *H* in Fig. 4).

The values for shrinkage, pore space of dry soil, and specific gravity are collected in Table III. In addition the moisture contents at the commencement of shrinkage measurements (column 5) and at the point of inflexion (column 7) are given in the customary unit of percentage by weight on dry material.

Table III.

	1	2	3	4	5	6	7	8	9
	Soil	Loss on ignition %	Clay %	Total shrinkage %	Moisture %	Residual shrinkage %	Moisture %	Pore space %	Specific gravity
A	Clay ...	9.5	90.5	130.0	75.9	8.6	16.7	22.5	2.643
B	Kaolin ...	12.4	52.8	30.0	45.2	nil	24.8	37.8	2.450
C	Clay ...	11.4	42.3	67.5	42.2	7.6	13.0	19.6	2.590
D	Subsoil ...	9.6	33.8	34.0	31.1	2.0	15.2	25.3	2.637
E	Harpden Common	10.5	25.2	37.5	43.5	10.3	29.5	33.5	2.445
F	Loam ...	8.3	14.8	21.0	28.4	2.2	18.7	30.3	2.567
G	Sandy ...	8.3	5.3	9.5	25.5	2.6	21.4	33.5	2.549
H	Peaty ...	27.0	—	85.5	101.8	18.2	50.5	44.9	2.265

An examination of Table III leads to the conclusion that, except in the case of kaolin, the total shrinkage is linked with the clay content and the residual shrinkage with the organic content (loss on ignition). One may suppose that the residual shrinkage depends upon the presence of films of colloidal material round the solid particles. This forms small pads between the particles when the first stage of shrinkage has brought them into contact. Owing to the highly colloidal nature of these pads they would not part with their water until the later stages of the drying of the soil, that is to say, their part in the shrinkage would be played after air began to replace water in the soil pores. This is the region of residual shrinkage. A very small amount of material would suffice to play this part if it were of a highly colloidal nature. Supposing the colloid to be uniformly distributed round uniform spheres in open packing a simple calculation shows that a decrease in volume of the colloid due to drying would be accompanied by a decrease twice as large in the total (soil) volume¹. For example, if the residual shrinkage of a soil is 2 per cent.

¹ If r be the radius of the sphere and colloidal coating, and δr be the shrinkage in the latter, then the decrease in volume of colloid is $4\pi r^2 \delta r$, while the decrease in the volume of the circumscribing cube is $6 \cdot (2r)^2 \cdot \delta r$. This gives the ratio of colloidal decrease to total volume decrease as approximately one-half.

this would indicate that, at the point of inflexion, the proportion of colloidal material present is about 1 per cent. by volume. The proportion by weight would be naturally much smaller. One may imagine the transition from the sol to gel form to take place at or near the point of inflexion. The assumptions made in this paragraph can only crudely represent the actual processes taking place in shrinkage, but they will serve to illustrate the way in which residual shrinkage depends upon the colloidal content.

The clay fraction of the soil as a whole is only slightly colloidal compared with the substances postulated in the last paragraph. Its effect on the shrinkage will only be shown when it is present in the soil in relatively large quantities, when it acts as a general matrix for the larger

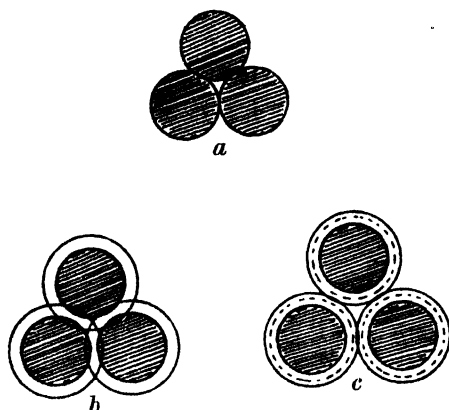


Fig. 5.

particles. It then imposes its own behaviour as regards shrinkage on the entire mass. Considering the porosity of dry clay it seems fair to assume that most of the particles composing it are large enough to be considered as individuals in a granular structure. These particles have the ability to take to themselves water and swell in the process. The simplest view to take of this is to suppose the particle to remain unchanged in itself, but to increase its effective diameter by acting as a centre of attraction round which a compressed water film gathers. The sketches shown in Fig. 5 will make this clearer. *a* shows the clay particles in rigid contact in the dry condition, the spaces between them being occupied by air. In *b* is depicted the state of affairs after the affinity of the particles for water has been partially satisfied. The circle drawn outside each particle represents the limit of its sphere of attraction. The space between the particles is supposed to be filled with water, and as

the circles overlap the water in the overlapping portions will be under the attraction of two or more particles. This will give the mass of clay considerable cohesion, but the films of water separating the particles will at the same time lend it plastic properties. Also the surface will not be sticky, except to surfaces that are wet. In *c*, Fig. 5, is shown the position when the affinity of the particles is fully satisfied, the outer spheres being just in contact. The cohesion of the mass will be much reduced, while the addition of any more water will tend to float off the particles from one another, inducing a state of stickiness and fluidity. We may assume that this third diagram represents the condition of the clay when the shrinkage measurements may be begun on it, as described earlier in the paper. In such case a simple calculation from the figures obtained for the clay separate indicates (assuming particles of a uniform size) that the adsorbed water film effectively increases the original diameter of the clay particle by about one-third. The essential argument in this paragraph is not altered if the particle is supposed to imbibe water like a small sponge or a sphere of gelatine.

The same hypothesis will explain the well-known increase in the plasticity of wet clay under high pressure (6). The water film round the particles is under greater and greater pressure as we approach the centre of attraction. Suppose that the dotted circles in *c*, Fig. 5, represent the distance at which the attraction of the particle induces a pressure in the water film of five atmospheres. Then, if the mass of clay be subjected to a pressure of five atmospheres, all the water outside the dotted circles will now act as free water. Thus the effective diameter of the particles is reduced, and their freedom relative to each other is much enhanced. In other words the plasticity is increased.

The absence of any residual shrinkage in kaolin (see *B*, Fig. 4) seems to indicate that the highly colloidal material which has been postulated is absent or rendered ineffective. The shrinkage curve in fact is the same as one would expect from a collection of clean crystalline particles. As soon as the shrinkage brings them into contact they form a rigid framework, which remains quite unaltered in outline during the further drying. It was thought interesting, therefore, to attempt to induce a residual shrinkage of the normal type by the admixture of small proportions of colloidal substances with kaolin. It would appear from a paper by Acheson (7) and the discussion which followed it, that such practices are common in the ceramic industry. The results of three such experiments are shown in Fig. 6. In the first case gelatine was added as a weak sol in the water used for working up the kaolin. Proportions of .5 per cent.

and 1.5 per cent. of the weight of kaolin were used, and the results are shown in curves III and IV. It will be noticed that the absence of residual shrinkage is almost as marked as in the case of kaolin alone (curve I), although the total shrinkage is much increased, being doubled in case IV. In explanation it must be supposed that the gelatine remains distributed throughout the water without any tendency to form films round the kaolin particles. The latter make the same rigid contact of crystalline surfaces as before, and the drying gelatine films form an independent network through the pore spaces of the kaolin.

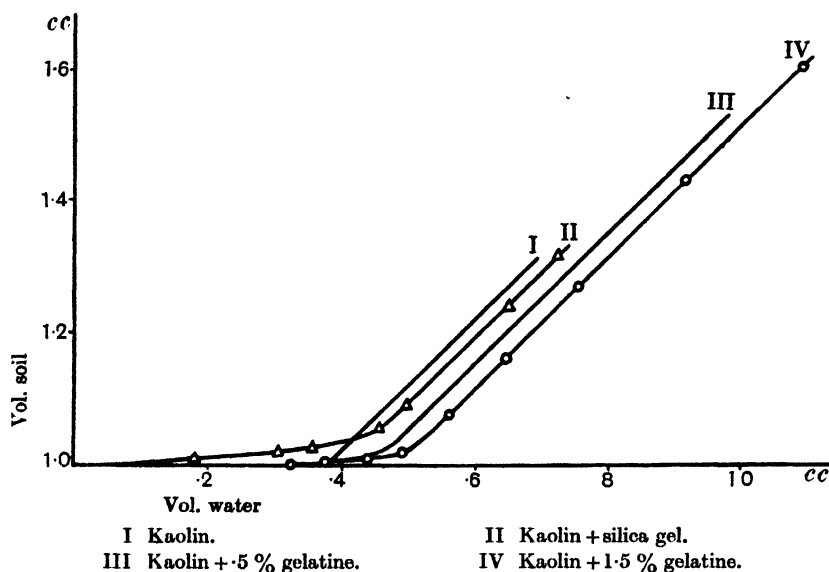


Fig. 6.

The increase in the pore space due to the addition of gelatine is most marked. In I the pore space (dry) is 37.8 per cent., while in IV it is increased to 48.5 per cent. The main reason for this is the higher moisture content at which the working-up and moulding of the material took place. Clay particles, particularly those of kaolin, are by no means spherical in shape. Upon microscopical examination of a suspension of kaolin the particles can be seen in Brownian movement and are distinctly flattened in shape. The streaky appearance of a clay suspension when eddies are induced in it by stirring is another proof of this flatness of shape. It follows that there will be a large range of different possible packings of the particles, with corresponding differences in pore space. Hence, a closer packing is likely to result where less water is used for

the incorporating process, since the particles are closer and more amenable to fitting in together than when more widely separated by water films. The same effect, as influencing soil cohesion, is noted by Johansson (*loc. cit.*).

The next test made was the addition of silica gel to kaolin. When the addition was made by simply incorporating the two together the result was in no way different from that in the case of gelatine mixtures. A second attempt was made in the hope of getting the gel precipitated upon the kaolin particles themselves. A suspension of kaolin was made in a dilute solution of sodium silicate, hydrochloric acid added, and the suspension dialysed. The shrinkage curve for this preparation is shown in II, Fig. 6. The amount of silica added was only a small fraction of 1 per cent. The type of shrinkage in the later stage has undergone the desired change, the residual shrinkage value being 3.2 per cent. in a total of 31.7 per cent. The change is attributed to the existence of pads of silica gel between the crystalline surfaces of the particles, as outlined in an earlier paragraph. A similar result was obtained on adding some clay separated from an arable soil to the kaolin, but in this case the amount required was very far in excess of the amount of the other colloids named. It is possible that, if the very finest part of the clay fraction, as separated by the workers at the U.S. Bureau of Soils⁽⁸⁾ and called by them "ultra clay," were used, very small additions to kaolin would suffice to bring about the change in its behaviour.

The absence of residual shrinkage as a property of a ceramic clay must be of great importance in that industry. Over the last stages of drying the internal forces in the material become large, and it becomes very resistant to change in shape. If shrinkage is going on at this stage any inequality in drying will result in irregular forces tending to warp the shape of the clay or to rupture it. Such troubles will be avoided if shrinkage ceases at the same time that the large increase in cohesion sets in. It is suggested that measurements of shrinkage as outlined in this paper would form a useful test in the routine examination of ceramic clays. A very few readings would be sufficient to indicate the presence or absence of residual shrinkage.

Some attempts were made at tracing the soil volume curve back in the opposite direction, that is, tracing the soil swelling when a dry prism is gradually wetted. The two difficulties in the way are, first, that many soils crumble to pieces when wetted after drying, and second, the impossibility of ensuring even distribution of the added water. By using a fine spray some approximation to the last condition is obtained, except

in the earliest stages of wetting. Fig. 7 shows the results of such treatment in the case of subsoil *D*, the drying and wetting being repeated a second time. Cameron and Gallagher (*loc. cit.*) give a similar diagram for measurements on their soil column. It will be seen that the volume of the re-wetted soil is greater than that of the original at any point, due, no doubt, to the air which gets locked in the pore spaces. The volume is permanently increased when the soil prism is again dried. Also the moisture content of the re-wetted prism, when water-logged, is not so great as in the original puddled soil. An examination of Fig. 7 is, in fact, an interesting commentary on the loosening processes going on in a soil under natural conditions. It will be realised that it is important that the

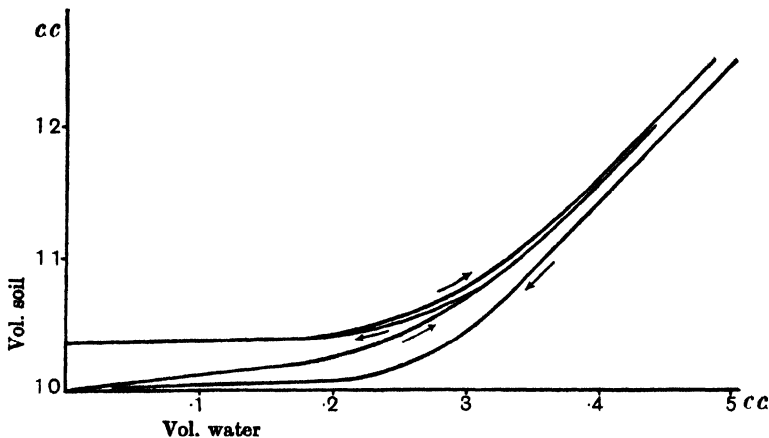


Fig. 7.

drying should extend below the point of inflexion so that air enters the soil pores before re-wetting takes place. Otherwise the wetting and drying would take place in a perfectly reversible manner, the volume changes being represented by movements to and fro on the upper part of the shrinkage curve. This corresponds to the well-known agricultural observation that a furrow slice of a heavy clay soil does not crumble properly under weathering until it has been dried below a certain moisture content. The loosening process does not come into full operation until the shrinkage has at least once extended to the point where air replaces water in the soil pores. In other cases than that shown, notably in a mixture of fine sand and clay, the departure of the swelling (re-wetting) curve from the shrinking (drying) curve was much greater, but these soils did not stand a second drying and wetting without going to pieces. In some exceptional cases where the organic content was high, there was very little swelling,

as the prism after drying did not wet readily. The heat of the water oven seemed to have caused irreversible changes analogous to those produced in the firing of clay. The dried colloidal coatings seemed to act as a permanent cement, and the soil block remained inert towards water.

SUMMARY.

(1) A new and simple method of measuring the shrinkage of moist soil on drying is described, which at the same time gives values for the pore space and specific gravity of the soil.

(2) Diagrams for a number of diverse soils are given, illustrating the character of soil shrinkage.

(3) The shrinkage is shown to take place in two stages in both of which there is a linear relationship to the moisture content.

(4) Tentative explanations of these two stages are advanced, based on the well-known colloidal-coating hypothesis, and confirmatory experiments described.

(5) By means of the method the effect of alternate wetting and drying of soil in producing a good tilth is illustrated.

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STUDIES IN CROP VARIATION.

II. THE MANURIAL RESPONSE OF DIFFERENT POTATO VARIETIES.

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(With Two Charts.)

1. INTRODUCTORY.

It is not infrequently assumed that varieties of cultivated plants differ not only in their suitability to different climatic and soil conditions, but in their response to different manures. Since the experimental error of field experiments is often underestimated, this supposition affords a means of explaining discrepancies between the results of manurial experiments conducted with different varieties; in the absence of experimental evidence adequate to prove or disprove the supposed differences between varieties in their response to manures such explanations cannot be definitely set aside, although we very often suspect that the discrepancies are in reality due to the normal errors of field experiments.

On the other hand, if important differences exist in the manurial response of varieties a great complication is introduced into both variety and manurial tests; and the practical application of the results of past tests becomes attended with considerable hazard. Only if such differences are non-existent, or quite unimportant, can variety tests conducted with a single manurial treatment give conclusive evidence as to the relative value of different varieties, or manurial tests conducted with a single variety give conclusive evidence as to the relative value of different manures.

In a recent experiment at Rothamsted twelve potato varieties were tested with six manurial treatments, and since the tests were carried out in triplicate the normal error may be evaluated with some accuracy. There is thus afforded a basis for comparing the discrepancies between the different varieties with those to be expected if all varieties had responded alike to the differences in manurial treatment. Both the general response to manurial treatment, and the general differences in the yield of varieties were well marked, so that the data are well suited to the present enquiry.

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The general question of the existence of differences in the response of varieties to manurial treatment cannot, of course, be answered from data respecting a single species. The principal purpose of the present note is to call attention to (i) the kind of data which is adequate to supply an answer in any particular case, and (ii) the statistical treatment by which such an answer can be elicited.

2. ARRANGEMENT OF EXPERIMENT.

The experimental work was carried out by Mr T. Eden, of this Station, and formed part of a larger investigation into the effects of fertilisers on potatoes.

AJAX	K OF K	NITHSDALE	GREAT SCOTT	DUKE OF YORK	S C B
GREAT SCOTT	DUKE OF YORK	ARRAN COMRADE	IRON DUKE	EPICURÉ	S C B
IRON DUKE	EPICURÉ	AJAX	K OF K	NITHSDALE	S C B
K OF K	NITHSDALE	GREAT SCOTT	DUKE OF YORK	ARRAN COMRADE	S C B
	UP TO DATE	KERR'S PINK	UP TO DATE	BRITISH QUEEN	S C B
	BRITISH QUEEN	TINWALD PERFECTION	EPICURÉ	KERR'S PINK	S C B
	KERR'S PINK	UP TO DATE	IRON DUKE	AJAX	S C B
	TINWALD PERFECTION	ARRAN COMRADE	BRITISH QUEEN	TINWALD PERFECTION	S C B

S = SULPHATE ROW C = CHLORIDE ROW
B = BASAL ROW

Diagram 1. Plan of experiment. Farmyard manure series.

The portion of land selected for the purpose had previously received uniform manurial treatment, thus avoiding the possibility of variation in yield due to the varying residual effect of different manurial systems. The total area used was quite small, being only .162 acres. This minimised the differences which might arise from variations in the natural fertility

of the soil, and from the position of the plots in the field. The smallness of the area used, and the uniform treatment of the land prior to the experiment, secured initial homogeneous conditions for all the rows as far as this was possible.

The total area was divided into two equal parts, one of which was used for the farmyard manure series, and the other for the series without farmyard manure. Each half was divided into 36 small plots and the twelve varieties of potatoes selected for the experiment were planted in triplicate on the "chess-board" system on both series. The accompanying plans show how the varieties were distributed over the experimental area in both the dunged and undunged series.

AJAX	K. OF K.	NITHSDALE	UP TO DATE	DUKE OF YORK	S C B
GREAT SCOTT	DUKE OF YORK	ARRAN COMRADE	IRON DUKE	EPICURE	S C B
IRON DUKE	EPICURE	AJAX	UP TO DATE	NITHSDALE	S C B
K. OF K.	NITHSDALE	GREAT SCOTT	DUKE OF YORK	ARRAN COMRADE	S C B
	KERR'S PINK	TINWALD PERFECTION	UP TO DATE	BRITISH QUEEN	S C B
	BRITISH QUEEN	ARRAN COMRADE	EPICURE	KERR'S PINK	S C B
	TINWALD PERFECTION	IRON DUKE	AJAX	GREAT SCOTT	S C B
		KERR'S PINK	BRITISH QUEEN	TINWALD PERFECTION	S C B

S = SULPHATE ROW

C = CHLORIDE ROW

B = BASAL ROW

Diagram 2. Plan of experiment. Series without farmyard manure.

It will be noticed from Diagram 2 that, in the series without farmyard manure, the variety K. of K. was only planted in duplicate instead of triplicate and allowance has had to be made for this irregularity in the data in applying the Statistical Method explained below.

Three rows of seven plants each were set on each plot: each row received the basal manuring of the series to which it belonged; and in

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addition, one row received a dressing of sulphate of potash, and another a dressing of muriate of potash.

The actual quantities of manure applied to the different types of rows are shown in the following table.

Table I.

	Farmyard manure tons per acre	Super. cwts. per acre	Sulphate of ammonia cwts. per acre	Sulphate of potash lbs. per acre	Muriate of potash lbs. per acre
Dunged Series:					
Sulphate row	15	4	1.5	184	—
Chloride row	15	4	1.5	—	147
Basal row	15	4	1.5	—	—
Undunged series:					
Sulphate row	—	6	2	244	—
Chloride row	—	6	2	—	197
Basal row	—	6	2	—	—

The actual weight of produce lifted from each of the 213 rows was recorded, and may be found in the *Report* of the Rothamsted Experimental Station for 1921 and 1922. From this data, two series of means were calculated: one giving the mean yield of each of the twelve varieties, irrespective of the manuring applied; and the other giving the mean yield of each system of manurial treatment irrespective of the variety grown. Table II shows the mean yield for each combination of manure and variety, together with the mean yield of each variety and each manurial system.

Table II.

Manurial treatment	Up to Date	K of K	Kerr's Pink	Timwald Perfection	Iron Duke	Great Scott	Ajax	British Queen	Nithsdale	Epicure	Arran Comrade	Duke of York	Mean yield
	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.
Dunged Series:													
Sulphate row	25.3	28.0	23.3	20.0	23.9	20.8	22.3	21.9	18.3	14.7	13.8	10.0	20.12
Chloride row	26.0	27.0	24.4	19.0	20.6	24.4	16.8	20.9	20.3	15.6	11.0	11.8	19.82
Basal row	26.5	23.8	14.2	20.0	20.1	21.8	21.7	20.6	16.0	14.3	11.1	13.3	18.62
Undunged Series:													
Sulphate row	23.0	[20.4]	18.2	20.2	15.8	15.8	12.7	12.8	11.8	12.5	12.5	8.2	15.33
Chloride row	18.5	[17.0]	20.8	18.1	17.5	14.4	19.6	13.7	13.0	12.0	12.7	8.3	15.47
Basal row	9.5	[6.5]	4.9	7.7	4.4	2.3	4.2	6.6	1.6	2.2	2.2	1.6	4.47
Mean yield	21.47	20.45	17.63	17.49	16.89	16.58	16.21	16.08	13.49	11.88	10.54	8.86	15.635

The figures enclosed within the square brackets are based upon two records only, but in calculating the marginal means, they have been given full weight. This eliminated the bias in the means concerned, due to the fact that the three missing quantities belonged to the series of one of the *highest* yielding varieties, and to the three *lowest* yielding manurial treatments.

3. ANALYSIS OF VARIATION ON THE SUM BASIS.

In order to make clear the method of the analysis of variation, we will first carry through the process on the assumption that the yield to be expected from a given variety grown with a given manurial treatment is the sum of two quantities, one depending on the variety and the other on the manure. This assumption is evidently an unsatisfactory one, but for a clear understanding of the method it is desirable to separate the difficulties of a more adequate theory, from the method adopted to analyse the variation.

The theory of this analysis depends on a well-known mathematical identity. If ξ, η, ζ stand for the yields of three parallel plots, x for the mean yield of the three, and \bar{x} the mean value of all the plots, then it is well known that

$$S \{(\xi - \bar{x})^2 + (\eta - \bar{x})^2 + (\zeta - \bar{x})^2\} \\ = S \{(\xi - x)^2 + (\eta - x)^2 + (\zeta - x)^2\} + 3S (x - \bar{x})^2.$$

Thus the sum of all the squares of deviations from the general mean may be divided up into two parts: one measures the variation within the triplicates, while the other measures the variation between triplicates differently treated. Further, if all the plots are undifferentiated, as if the numbers had been mixed up and written down in random order, the average value of each of the two parts is proportional to the number of degrees of freedom in the variation of which it is compared. Had the record been complete, 216 plots would have given 215 degrees of freedom; each triplicate contains two degrees of freedom in which its numbers may mutually differ, giving 144 for variation within the triplicates; while the 72 different combinations of variety and manure account for the remaining 71 degrees of freedom. Actually we have 69 triplicates and three duplicates, so that the total degrees of freedom are 212, of which 141 are within, and 71 between triplicate sets.

This analysis may be carried further if we wish to distinguish the effects of variety and manure. There are 5 independent differences among the manures, 11 among the varieties, while the remaining 55 show the differences between the varieties in their response to manurial treatment. To each of these classes can be assigned a definite fraction of the sum of the squares of deviations; thus, if a_1, a_2, \dots, a_{12} are the mean yields of the 12 varieties, b_1, b_2, \dots, b_6 the mean yields of the 6 manures,

$$3S (x - \bar{x})^2 = 18S (a - \bar{x})^2 + 36S (b - \bar{x})^2 + 3S (x - a - b + \bar{x})^2.$$

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In Table III is shown the analysis of the variation into these four classes; the mean square deviation is found by dividing the sum of squares in each class by the number of degrees of freedom, while the standard deviation is shown in the last column. When this value is significantly greater than the standard deviation of the differences between parallel plots, we may conclude that the corresponding effect is not due to chance.

• Table III.

Variation due to	Degrees of freedom	Sum of squares	Mean square	Standard deviation
Manuring	5	6,158	1231.6	35.09
Variety	11	2,843	258.5	16.07
Deviations from summation formula	55	981	17.84	4.22
Variation between parallel plots ...	141	1,758	12.47	3.53
Total	212	11,740	—	—

In comparing the standard deviations in the last column we may use the fact that 3.53, for example, has the same accuracy as if it had been determined from a sample of 142; the variance of its natural logarithm is therefore $\frac{1}{2 \times 141}$. Thus, to test if the deviations from the summation formula are significantly greater than would occur by chance, we compare the difference of the logarithms with its standard error, namely $\sqrt{\frac{1}{2 \times 142} + \frac{1}{110}}$:

$\frac{1}{2 \times 142} =$	.003546	$\log_e 4.22 =$	1.4398
$\frac{1}{110} =$	.009091	$\log_e 3.53 =$	1.2613
Sum	.012637	Difference	.1785 \pm .1124
Standard Error	.1124		

The difference in the logarithm thus exceeds its standard error, but not sufficiently to be significant; while the effects both of manuring and of variety are very strongly marked, and clearly significant.

4. TRIAL OF PRODUCT FORMULA.

The above test is only given as an illustration of the method; the summation formula for combining the effects of variety and manurial treatment is evidently quite unsuitable for the purpose. No one would expect to obtain from a low yielding variety the same actual increase in yield which a high yielding variety would give; the falsity of such an assumption is emphasised by the fact that the expected values $(a + b - \bar{x})$ calculated on such an assumption, are often negative in the unmanured series. A far more natural assumption is that the yield

should be the product of two factors, one depending on the variety and the other on the manure. As a preliminary test of this assumption we may take the formula $\frac{ab}{\bar{x}}$; the computed yields from each combination of variety and manure are shown in Table IV.

Table IV.

	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}	a_{12}
b_1	27.6	26.3	22.7	22.5	21.7	21.3	20.9	20.7	17.4	15.3	13.6	11.4
b_2	27.2	25.9	22.3	22.2	21.4	21.0	20.5	20.4	17.1	15.1	13.4	11.2
b_3	25.6	24.4	21.0	20.8	20.1	19.7	19.3	19.1	16.1	14.1	12.5	10.6
b_4	21.0	20.0	17.3	17.2	16.5	16.3	15.9	15.8	13.2	11.6	10.3	8.7
b_5	21.2	20.2	17.4	17.3	16.7	16.4	16.0	15.9	13.4	11.8	10.4	8.8
b_6	6.1	5.9	5.0	5.0	4.8	4.7	4.6	4.6	3.9	3.4	3.0	2.5

The computed values are now more variable than before, but agree more closely with the observations. Since the formula $\frac{ab}{\bar{x}}$, where a and b are the variety and manurial means, is not the best fitting product formula, this circumstance speaks strongly in favour of the product as against the summation formula. If we now make out a table showing the subdivision of the variation, it will be seen that the total no longer tallies with the sum of the squares of the 213 deviations from the general mean, thus indicating that we are not using a least square solution, and that the fit can be improved.

Table V.

Variation of	Degrees of freedom	Sum of squares	Mean square	Standard deviation
Computed values (manures and varieties)	16	9,348	—	—
Deviations from product formula ...	55	873	15.87	3.98
Parallel plots	141	1,758	12.47	3.53
Total	212	11,979	—	—

Table V shows that with the product formula there is even less indication of varietal differences in manurial response. In the present material evidently the varieties show no difference in their reaction to different manurial conditions. The method, however, is at this stage unsatisfactory, for, in dividing up the variation according to the different groups of degrees of freedom, we assume that adequate methods of fitting have been employed. In the present case an improved fit can only strengthen our conclusion, but it is necessary to indicate how an adequate fit can be obtained when the conclusions are less clear.

5. THEORY OF FITTING A PRODUCT FORMULA.

Given any set of positive values $x_{pp'}$, where p takes integral values from 1 to n , and p' from 1 to n' , we require to find values $a_1, a_2, \dots, a_n, b_1, b_2, \dots, b_{n'}$, such that

$$\sum_1^n \sum_1^{n'} (x_{pp'} - a_p b_{p'})^2$$

is a minimum. Differentiating with respect to a_p , we have

$$\sum_1^{n'} (b_{p'} x_{pp'}) = a_p \sum_1^n (b_{p'}^2) \quad n \text{ equations} \quad \dots\dots(I),$$

$$\sum_1^n (a_p x_{pp'}) = b_{p'} \sum_1^n (a_p^2) \quad n' \text{ equations} \quad \dots\dots(II).$$

From either of these sets of equations we can deduce

$$\sum_1^n \sum_1^{n'} (a_p b_{p'} x_{pp'}) = \sum_1^n (a_p^2) \cdot \sum_1^{n'} (b_{p'}^2) = \lambda,$$

showing that we have only $n + n' - 1$ independent equations; as is obvious if we consider that in any solution we may multiply all the values of a , and divide all the values of b by any factor, without affecting the products.

Knowing λ , the minimum value sought may be directly calculated, for

$$\sum_1^n \sum_1^{n'} (x_{pp'} - a_p b_{p'})^2 = \sum_1^n \sum_1^{n'} (x_{pp'}^2) - \lambda \quad \dots\dots(III).$$

At this point two courses are open: (i) we may obtain an approximate solution from equations (I) and (II); by inserting in equation (I) the values of b previously used, we obtain a new series a_p , using in fact approximately the right weights, instead of equal weights as in the previous calculation; then from this new series, a_p , we recalculate b_p by equation (II); (ii) we may eliminate a_p and b_p , and obtain an equation for λ . This latter process is exceedingly laborious and we shall only use it so far as to show that an adequate approximation is obtained by the first method.

By the first method the following values of a_p, b_p , and their products were obtained:

Table VI.

	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}	a_{12}
	20.98	20.48	17.55	16.94	16.94	17.02	16.24	15.99	13.91	12.01	10.50	9.01
b_1	1.290	27.1	26.4	22.6	21.9	22.0	20.9	20.6	17.9	15.5	13.5	11.6
b_2	1.270	26.6	26.0	22.3	21.5	21.6	20.6	20.3	17.7	15.3	13.3	11.4
b_3	1.187	24.9	24.3	20.8	20.1	20.2	19.3	19.0	16.5	14.3	12.5	10.7
b_4	.983	20.6	20.1	17.3	16.7	16.7	16.0	15.7	13.7	11.8	10.3	8.9
b_5	.981	20.6	20.1	17.2	16.6	16.7	15.9	15.7	13.6	11.8	10.3	8.8
b_6	.300	6.3	6.1	5.3	5.1	5.1	4.9	4.8	4.2	3.6	3.2	2.7

The variation of these computed values, and of the deviations of the observed values from them are shown in the following table.

Table VII.

Variation of					Degrees of freedom	Sum of squares	Mean square	Standard deviation
Computed values (manures and varieties) }					16	8,966	—	—
Correction for mean }					—	169	—	—
Deviations from product formula ...					55 *	847	15.40	3.92
Parallel plots					141	1,758	12.47	3.53
Total					212	11,740	—	—

The deviations from the product formula are diminished; the solution is certainly very near the best possible, since the total of the sums of squares now agrees with the true value. The mean of the computed values exceeds that of the observed value by .025, and the correction inserted above is 72 times the difference of the squares of these two values. In order further to demonstrate that the solution obtained cannot be sensibly improved it will be necessary to consider the exact method of solution.

If we use equation (I) to eliminate the a_p from equation (II), there result equations of the form

$$\sum_1^{n'} \{b_p \cdot \sum_1^n (x_{p1} x_{pp'})\} = \lambda b_1,$$

or, writing
$$c_{rs} = \sum_1^n (x_{pr} x_{ps}),$$

the equations are

$$(c_{11} - \lambda) b_1 + c_{12} b_2 + \dots + c_{16} b_6 = 0,$$

$$c_{12} b_1 + (c_{22} - \lambda) b_2 + \dots + c_{26} b_6 = 0,$$

$$\dots \dots \dots$$

$$c_{16} b_1 + c_{26} b_2 + \dots + (c_{66} - \lambda) b_6 = 0,$$

which, by elimination of the b_p , give as an equation for λ

$$\begin{vmatrix} (c_{11} - \lambda) & c_{12} & c_{13} & \dots & c_{16} \\ c_{12} & (c_{22} - \lambda) & c_{23} & \dots & c_{26} \\ \dots & \dots & \dots & \dots & \dots \\ c_{16} & c_{26} & c_{36} & \dots & (c_{66} - \lambda) \end{vmatrix} = 0,$$

an equation of the 6th degree, which may be expanded in the form

$$\lambda^6 - S(c_{pp}) \lambda^5 + S \left\{ \begin{vmatrix} c_{pp} & c_{pq} \\ c_{pq} & c_{qq} \end{vmatrix} \right\} \lambda^4 - S \left\{ \begin{vmatrix} c_{pp} & c_{pq} & c_{pr} \\ c_{pq} & c_{qq} & c_{qr} \\ c_{pr} & c_{qr} & c_{rr} \end{vmatrix} \right\} \lambda^3 + \dots$$

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It is fortunately not necessary to evaluate the whole of this equation, since the terms are of diminishing importance. Since

$$S(c_{vv}) = \sum_1^n \sum_1^{n'} (x_{vp}^2),$$

and λ is slightly less than this quantity, we may obtain a succession of approximations for λ with alternately positive and negative errors, by taking account of the successive terms of the equation. The first terms are

$$\lambda^6 - 20,928.01\lambda^5 + 5,853,407.6454\lambda^4 - 597,335,955\lambda^3 + \dots,$$

from the first two terms we have

$$\lambda = 20,928.01 \qquad 20,928.01 - \lambda = 0;$$

the error being positive; taking in the 3rd term we find

$$\lambda = 20,644.48 \qquad 20,928.01 - \lambda = 283.53;$$

with a negative error; with the 4th term

$$\lambda = 20,645.90 \qquad 20,928.01 - \lambda = 282.11;$$

showing how rapidly an approximation is attained. Since the error of this last value is positive, the sum of the squares of the deviations cannot be less than 282.11, or the value in Table VII less than 846.

Since the value obtained from the approximate method was 847, this must be substantially the true value. The true subdivision of the variation must therefore be that given in Table VII.

Testing the significance of the deviation

log 3.92	1.3661
log 3.53	1.2163
	.1048 ± .1124.

CONCLUSIONS.

(1) The data show clearly significant variation in yield due to variety and to manurial treatment.

(2) There is no significant variation in the response of different varieties to manure.

(3) The yields of different varieties under different manurial treatment are better fitted by a product formula than by a sum formula.

(4) For the purposes of analysing the variation the product formula may be obtained by successive approximation from equations (I) and (II); the exact method of solution should not be necessary in any ordinary case.

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THE HYDROGEN-ION CONCENTRATION OF HEAVY ALKALINE SOILS.

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1. INTRODUCTION.

IN connection with the systematic examination of the soils of the Sudan, the hydrogen-ion concentration has been determined of a large number of samples taken from a wide area, and with a single exception, all those examined up to the present have been alkaline, the pH value being invariably over 8 and often over 9.

The present communication deals with the methods used in this work and the effect of varying conditions on soil reaction. As will appear, the details of the technique materially affect the results obtained and it is considered absolutely essential that they should always be specified in giving numerical results, which otherwise cannot be used for comparison with those obtained by other workers.

The degree of accuracy which we have aimed at in most cases is 0.05 pH : this is quite easily obtainable and is necessary in dealing with alkaline soils owing to the comparatively small effect on the pH produced by amounts of sodium carbonate usually considered objectionable. The fact that pH is an exponential function is easily overlooked: an increase of 0.1 corresponds to an increase of 25 per cent. in the hydroxyl-ion concentration and may correspond to an even larger amount of sodium carbonate in the soil.

2. THE ELECTROMETRIC METHOD.

All measurements have been made with a Leeds and Northrup potentiometer and galvanometer using a Weston standard cell: a Clark's calomel electrode with $N/10$ potassium chloride has been used in all cases for soil suspensions but for certain measurements with aqueous solutions the Hilderbrand electrode in conjunction with a saturated potassium chloride calomel electrode has proved more rapid. Unless

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stated to the contrary it will be understood that the *N/10* electrode has been used in the work now described.

The galvanometer gives a sensible deflection with 0.0001 volt under favourable circumstances (e.g. freshly platinised electrodes working in a clear aqueous solution): in ordinary work at least one-tenth of this sensibility is always attained, corresponding to 0.017 in the *pH* value. The *pH* value is calculated from the observed E.M.F. by the formula given by Clark (1):

$$pH = \frac{\text{Observed E.M.F.} - \text{E.M.F. of the calomel half cell}}{0.00019837T}$$

For the E.M.F. of the *N/10* electrode we have used the value 0.337, as our working temperatures lie between 25° and 30°. The temperature is taken in the cell itself immediately after the reading: as *pH* is directly proportional to absolute temperature, a whole degree affects it by only 1 part in 300 and a thermostat is unnecessary for making the measurements, although the temperature at which the extracts are made affects the result, especially when the time of extraction is prolonged. The greatest difference we have observed due to this cause is one of 0.24 between the *pH* of extracts made for 24 hours at 8° C. and 37° C. respectively: for ordinary variations in room temperature, the effect may be disregarded. The potentiometer, Weston cell, calomel and hydrogen electrodes stand on the same sheet of lead which is earthed by being connected to the laboratory water pipe.

The hydrogen is generated in a Kipps apparatus from commercial zinc and hydrochloric acid and passes through the usual purifying solutions of mercuric chloride, potassium permanganate, alkaline pyrogallol, and sulphuric acid, into a gas holder: from this it passes through alkaline pyrogallol, acid and water to the electrode vessel as required.

The electrodes are platinised in the usual way as frequently as their appearance indicates that it is desirable.

3. THE INDICATOR METHOD.

Clarke and Lub's series of indicators and buffer solutions are used, the only difficulty being that of obtaining sufficiently accurate comparisons when the soil suspensions are turbid: this is, of course, frequently the case with our alkaline soils.

For rapid approximate work we have occasionally used the "spot" method (2) in which a few grams of the soil are placed on a white glazed tile and moistened with the indicator.

4. DETERMINATION OF THE *pH* OF SOILS.

Before settling the details of the method of making the soil-water mixtures for the determinations, we have had to ascertain how far the following statements apply to our soils:

(a) Gillespie and Hurst⁽³⁾ lay great stress on the necessity of making electrometric determinations on soil suspensions and not on clear extracts, the values obtained from extracts free or nearly free from soil particles being "indefinite and meaningless."

(b) The same authors (*loc. cit.*) indicate that normal quantities of nitrates may vitiate results obtained electrometrically. They state that "as far as is known, extracts of normal soils cannot be measured electrometrically, but only by the indicator method."

(c) It is frequently assumed that the manner of making the soil suspension or extract, *i.e.* the soil-water ratio and the time of extraction, exerts little influence on the result. Thus Sharp and Hoagland⁽⁴⁾ and Gillespie and Hurst (*loc. cit.*, p. 228) state that there are comparatively insignificant changes in H-ion concentration when widely varying proportions of water to soil are used¹.

In regard to all three questions, our experience is the reverse of that of the authors quoted. We find that a clear or moderately clear soil extract obtained by centrifuging gives sharp readings by the electrometric method and a degree of agreement with the colorimetric method as great as the accuracy obtainable which the latter permits. On the other hand irregular results are quite likely to occur when the soil particles are present, unless the conditions are such that equilibrium has been reached between liquid and solid phases. The effect of nitrates on the *pH* of soils is dealt with later, but disturbances on this account are not more pronounced with clear extracts than in thick suspensions, and provided sufficiently clear solutions can be obtained to permit of good colorimetric determinations being made, the three methods give concordant results such as are illustrated by the figures given in Table I for the *pH* of mixtures made with one part of soil to five of water.

Table I.

Sample No.	Electrically on thick suspension	Electrically on centrifuged extract	Colorimetrically on centrifuged extract
10195	9.42	9.43	9.3
9210	8.49	8.43	8.4
9783	8.73	8.69	8.5
9791	9.01	8.93	8.8

¹ Some of these authors' own results, however, are not in agreement with this statement.

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Filtration of the mixture is inadvisable as filters are very likely both to react with the alkali in the extract and to give up to it any soluble material they contain. Ordinary filter paper, even after long washing, still yields noticeable amounts of electrolyte on further treatment with distilled water: it also reacts sufficiently with solutions of sodium carbonate and silicate to reduce the *pH* to a marked extent. If, however, a clear extract can be prepared without filtration, its reaction is the same as that of the turbid suspension.

5. PREPARATION OF THE SOIL SUSPENSION OR EXTRACT.

To settle a method by which the extract or suspension is to be prepared is a matter of very great difficulty owing to the influence on the result of the proportion of water used and the time of extraction. The difficulty has long been recognised by workers on soil solutions: thus Schreiner and Failyer(5) state that "if comparable results are to be obtained, it is essential in preparing the soil extract to follow as nearly as possible a uniform procedure. The volume of water used and the time of its action are necessarily conventional." This has been the general experience in determining the amount of soluble matter of the soil, and in estimating, by titration methods, the amount of sodium carbonate, and it is therefore surprising that so little stress is laid on this important variable in *pH* determinations.

Prolonged contact with water continually brings fresh material into solution. This has been shown by Bouyoucos(6,7) by the gradual increase in freezing-point depression and can also be followed by the diminution of the electrical resistance of soil-water mixtures with time: the effect of short periods of time on hydrogen-ion concentration has also been recorded by Kelley and Brown(8). Whilst this increase of concentration of the soil extract is observed for all soils, its influence on the hydrogen-ion concentration is by no means uniform, as this is affected not so much by the amount as by the nature of the soluble material. The effect of gradually bringing salts into solution is dealt with later in paragraph 10: it raises the hydrogen-ion concentration, whilst the slower passage into solution of sodium carbonate or silicate reduces it. The resultant of these reactions at any time will obviously depend on the composition of the soil.

The effect of the time of extraction is illustrated by the following results obtained by putting 20 gram portions of air-dried soil in 100 c.c. of water and determining the *pH* and electrical resistance at suitable intervals. A three hour test showed that no difference resulted from

continuously shaking the mixture instead of merely leaving it to stand after a short initial shaking.

Table II.

Cotton soil No. 6640 (A).

Time	1 hour	Days				
		1	2	4	8	16
Specific resistance at 25° in ohms	3500	2727	2501	2403	2070	1692
pH (mean of duplicates)	9.17	8.77	8.75	8.78	8.64	8.48

It will be noticed that the pH has diminished by over 0.6 during a fortnight, corresponding to a reduction of the hydroxyl-ion concentration to one-fifth of its initial value, whilst at the same time the change in resistance indicates a large increase in total electrolytes.

The opposite effect is shown by the same soil after leaching it until the specific resistance of its extract was brought up to about 10,000 ohms.

Table III.

Time	2 hours	Days					
		1	2	4	8	16	32
pH	8.13	8.29	8.28	8.58	8.51	8.46	8.35

In this case the hydroxyl-ion concentration has been doubled during the first four days; it subsequently decreases.

6. EFFECT OF VARYING THE PROPORTIONS OF SOIL TO WATER.

The effect of varying the amount of water used in making the soil extract influences the hydroxyl-ion concentration in a complicated way. Not only does it affect the amount of electrolyte yielded by the soil owing to direct solvent action, but increasing the amount of water also causes variations owing to increasing dissociation and hydrolysis, whilst simple dilution of course reduces the concentration of the hydroxyl-ion.

This effect has been shown by Kelley and Brown⁽⁸⁾ and is further demonstrated by the following results for duplicate determinations of the pH of soil extracts made with proportions of water varying from 1 to 160, the time of extraction being 1 to 2 hours.

Table IV.

Soil 6640 (A).

Parts of water to 1 of soil	1	5	10	20	40	80	160
pH (mean of duplicates)	8.60	9.18	9.33	9.42	9.34	9.24	8.98

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Presumably the maximum amount (not concentration) of hydroxyl-ion has been reached at a soil-water ratio of 1 to 80, as the next twofold dilution produces a reduction of hydroxyl-ion concentration from 1.8×10^{-5} to 0.95×10^{-5} —a ratio of nearly 2 to 1. On the other hand, the maximum hydroxyl-ion concentration is found to a soil-water ratio of 1 to 20, where it is 2.6×10^{-5} .

7. COMBINED EFFECT OF TIME OF EXTRACTION AND PROPORTION OF WATER.

To obtain information as to this, suspensions were made with three different soils varying both the proportion of water and the time of extraction. The abbreviated results are given in the next table:

Table V.

Time of extraction Parts of water to 1 of soil	Cotton soil 6640 (Z)		Blue clay soil 9320		Red sandy soil	
	1 hour	2 days	1 hour	2 days	1 hour	2 days
1	9.05	8.85	8.94	8.44	8.00	8.27
5	9.45	9.05	8.50	8.46	8.10	8.13
25	9.66	9.36	8.11	8.38	7.94	8.40

It will be observed that each soil exhibits its highest *pH* value under a different set of conditions and this emphasises sufficiently the necessity of exactly specifying the two variables under consideration.

The practical question arises as to what it is that we really wish to determine in a soil. There is something to be said in favour of choosing those conditions which yield the highest hydrogen or hydroxyl-ion concentration, as then we know the worst with which the plant or soil organisms may have to contend. This procedure would be analogous to that of ordinary mechanical analysis, which for example, by no means gives the proportion of fine particles actually in the soil in the field but indicates the number which *might* result under a treatment producing complete deflocculation—it tells us the worst which may happen. The difficulty with regard to *pH* is that a series of measurements would be required for each soil in order to determine which soil-water ratio and time of extraction produced the highest *pH* value, and the labour thus involved would make such a method impossible of application to routine examinations.

Another plan would be to make the observations on what is often styled the “real soil solution,” that is the solution which can be removed from a soil containing about as much water as is found in field conditions.

Such soil solutions can be obtained by pressure, or more easily by displacement by means of water or alcohol: the method has recently been investigated by Parker (9) and we have used it by placing about 500 grams of air dry soil in a percolator, adding carefully 25 per cent. of water and subsequently displacing the soil solution with alcohol. With heavy soils, the process is slow, as long as 48 hours being sometimes required to obtain 25 c.c. of solution. This would certainly be most inconvenient as a routine method and we have come to the conclusion that a soil-water ratio of 1 to 5 and a time of extraction 1 hour is on the whole the most satisfactory for routine work. We are supported in this by the work of Hoagland, Martin and Stewart (10), who found that 1 to 1 or 1 to 5 extracts made as rapidly as is compatible with thorough mixture, remain in equilibrium with the soil during the working period.

8. DISTURBING EFFECT OF NITRATES.

In paragraph 4, reference was made to the possibility of disturbing effects arising owing to the presence of nitrates, which are slowly reduced by hydrogen in the presence of platinum black: thus a neutral 1 per cent. solution of sodium nitrate, through which hydrogen was slowly passed for five hours in the presence of a few square cms. of platinised platinum foil, attained a *pH* of over 10 and gave a heavy precipitate with Nessler's reagent. Such high concentrations of nitrate render satisfactory readings by the electrometric method impossible, but we find that weak solutions give good readings and in accordance with what would be expected from those obtained with inert salt solutions. Examples are given in the table below:

Table VI

Soil 10345 containing no nitrate: 1 part of soil to 5 of solution									
Per cent. sodium nitrate	0	0.004	0.01	0.04	0.1				
added to soil extract									
Corresponding to parts per	0	200	500	2000	5000				
million in the soil									
<i>pH</i> ...	...	9.42	9.41	9.34	9.10	Bad reading			

The slight alteration towards acidity is obviously due to the ordinary effect of an inert salt (which is dealt with in the next paragraph): only when the amount of nitrate in the soil reaches a figure quite beyond that for a normal soil does the disturbing effect manifest itself. Our results therefore confirm the statement of Sharp and Hoagland (*loc. cit.*, p. 128) and Plummer (11) as to the non-interference of nitrates.

9. EFFECT OF ELECTROLYTES.

Among the conditions which exert an important influence on soil reaction, the nature and amount of electrolytes, such as may be added

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in the form of fertilisers or as dissolved material in irrigation water, occupy a prominent place, and we have therefore examined the effect of some of them on the *pH* of one of our typical soils. The effect produced may be due to one or more of the three important properties possessed by the soil minerals, these substances being (a) amphoteric or buffer substances¹, (b) adsorbing substance, and (c) capable of undergoing base replacement.

As an amphoteric substance, clay—the most reactive of the soil fractions—neutralises both acids and alkalies, and so shifts the hydrogen-ion concentration towards the neutral point. On the other hand, the addition of a neutral salt causes the replacement of aluminium and iron in addition to sodium, potassium or calcium, and since aluminium salts of strong acids are hydrolysed to a considerable extent² the hydrogen-ion concentration becomes thereby increased: the effects produced by salts of calcium or ammonium are greater than those of sodium or potassium as they are salts of weaker bases.

Water extracts of soils containing electrolytes are found on analysis to contain calcium and iron and the following experiment is quoted as an example of the comparative ease with which the replacement takes place. Two litres of a purified clay suspension containing 10 grams of dry clay were treated with 1.35 grams of calcium sulphate for 24 hours at the ordinary temperature and the mixture filtered: on analysis, the filtrate was found to contain 0.12 grams of iron and aluminium calculated as oxide, and .105 gram of silica.

The following tables give the collected results³ obtained by leaving 1 part of soil to stand in contact with 5 parts of solution for 24 hours at the room temperature. All the measurements were made electrometrically except in the case of the nitrate solutions.

Table VII.

<i>pH</i> of Cotton soil with acid and alkali.							
Per cent.	...	...	...	0	0.1	0.5	1.0
Sodium hydroxide	{ alone	...	—	—	12.24	12.86	13.12
	{ with soil	...	8.99	—	11.03	12.41	12.80
Sodium carbonate	{ alone	...	—	—	10.97	11.17	11.26
	{ with soil	...	9.13	—	9.55	9.96	10.27
Sulphuric acid	{ alone	...	—	—	1.86	1.23	0.92
	{ with soil	...	8.99	—	7.84	3.49	2.55

¹ These terms are of course not synonymous, but the properties here referred to may be accounted for on either hypothesis.

² A solution containing 0.05 per cent. of potash alum was found to have a *pH* of 4.1.

³ Results obtained by the action of potassium, sodium, and barium chloride on acid soils are given by Sharp and Hoagland (*loc. cit.*, p. 132).

The neutralising or "buffer" action of the soil is well illustrated by these figures. Table VIII gives the results for salt solutions.

Table VIII.

pH of Cotton soil 6640 (Z) with Salts.

Per cent. ...	...	0	0.1	0.5	1.0	5.0
Sodium chloride ...	...	8.92	8.43	8.18	7.94	7.84
Sodium nitrate ...	...	9.0	8.5	8.0	7.9	7.8
Sodium sulphate ...	...	9.04	8.68	8.27	8.15	8.05
Calcium chloride ...	...	9.17	8.51	7.96	7.81	7.50
Ammonium sulphate	9.00	8.19	7.56	7.51	7.27	

By interpolating between these figures, it is found that the effect of chemically equivalent quantities of sodium chloride, nitrate and sulphate are very nearly the same.

10. RESIDUAL EFFECT OF ELECTROLYTES IN THE SOIL.

The reaction of a mixture of a soil with a neutral salt of sodium shifts in the direction of acidity, the change increasing with time. The reactions involved are very slow at room temperature and it is doubtful whether true equilibrium is ever reached in ordinary work or even in the field under changing conditions of moisture, but they will probably effect the slow production of a modified soil complex in which part of the aluminium has been replaced by sodium¹, any tendency of this body to pass into solution being checked by the high concentration of sodium ions already present. If, however, the salt solution, which contains the dissolved aluminium, be removed, sodium salts of weak acids (*e.g.* simple or complex silicates) can pass into solution in pure water and furnish alkaline solutions.

The production of a strongly alkaline soil by treating with sodium chloride solution and subsequently removing the salt by washing, is dealt with by Prescott (12), who attributes the alkalinity to sodium carbonate produced by reactions in which calcium carbonate of the soil is involved. Since however we have found that some soils which contain no calcium carbonate become more alkaline on treatment with water, the formation of sodium silicate or aluminate must also be regarded as a possible source of alkali, especially as all the filtered extracts of alkaline soils we have examined have been found to contain silica and aluminium. Of course the presence of sodium carbonate in a soil is hardly ever proved; it is presumed present whenever hydroxyl-ions are found by a titration or other method.

¹ Or potassium or calcium.

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The following table gives the *pH* of soils which have been subjected for some time to the action of salt solutions and then washed with dilute alcohol (to prevent deflocculation) until no salt should be detected in the filtrate.

Table IX.

Soil 6640; strength of salt solution 5 per cent.; 1 part of soil to 5 of solution or water.

<i>pH</i>	Sodium chloride	Sodium sulphate	Sodium nitrate	Ammonium sulphate	Calcium chloride
Soil-water after 24 hrs.	8.92	9.04	9.0	9.00	9.17
Soil-salt solution	{ 1 day 7.84	{ 1 day 8.05	{ 1 day 7.8	{ 1 day 7.45	{ 1 day 7.50
Soil-salt solution	{ 7 days 7.70	{ 8 days 7.93	{ 10 days —	{ 7 days 7.55	{ 7 days 7.41
Washed residual soil	9.88	9.20	9.93	8.86	8.80

It will be seen that the washing causes a large increase in alkalinity in each case: the final alkalinity of the soil depends upon the salt used and may be greater or less than that of the original soil.

A similar effect is shown by merely leaching a soil containing soluble salts. Thus No. 10292 contained about 1.8 per cent. of soluble salts and the usual 1 to 5 extract had a *pH* value of 7.95: after two washings (by shaking with water and removing the clear extract in the centrifuge), the soluble salt content fell to 0.04 per cent. and the *pH* rose to 9.39.

This soil contained 0.9 per cent. calcium carbonate (as calculated from the amount of carbon dioxide found). The experiment was repeated with soil No. 7804 containing no calcium carbonate (*i.e.* less than 0.001 per cent.): with one washing the *pH* rose from 7.47 to 7.91.

11. THE DRYING OF ALKALINE SOILS.

The effect of temperature and of desiccation in soils is particularly important in an arid climate owing to the changes which may be produced in the soil by the baking effect of the hot summer sun: flocculation, partial sterilisation, and destruction of objectionable organic compounds may result from fallowing and we have been interested in seeing whether the alkalinity is likely to alter from the same cause as far as can be indicated by laboratory experiments.

One of the observations made early in this connection was that an oven-dried alkaline soil always gives a lower *pH* than the soil in its original condition, the determination being made according to the standard method, *i.e.* on a 1 to 5 suspension allowed to stand 1 hour.

Examples of the results are given below, some of the determinations being made with soils moistened with solutions of sodium hydroxide or carbonate in order to obtain a high initial *pH* value.

Table X.

Before drying	9.38	9.52	9.74	11.02	13.16
After drying at 100°	9.25	9.28	9.48	10.43	12.41

The only exception to this behaviour were cases in which the soil was made alkaline with strong solutions of sodium carbonate; for example, with a 5 per cent. solution, the initial pH of 10.22 rose to 10.52 on drying. Such results were shown to be due to the escape of carbon dioxide during the process of drying, this reaction taking place slowly even at the temperature of the room.

Apart from this, the general reduction of pH on oven-drying is probably due to the accelerated effect of the electrolytes caused by increase of temperature and concentration, since the same value is obtained for the undried and dried samples if both are left in contact with water for a sufficiently long time.

Table XI.

Cotton soil 10195.

Treatment for 24 hrs.	Time of extraction								
	1 hour			1 day			1 week		
	Un- dried	Dried	Diff.	Un- dried	Dried	Diff.	Un- dried	Dried	Diff.
None	9.43	9.06	0.37	9.32	8.95	0.37	8.90	8.90	0.00
Wetted with water ...	9.54	9.18	0.36	9.21	9.15	0.06	8.63	8.66	0.03
Wetted with $N/10 Na_2CO_3$	9.77	9.52	0.25	9.56	9.46	0.10	8.89	8.81	0.08
Wetted with $N/10 NaOH$	11.58	11.17	0.41	11.45	11.38	0.07	11.25	11.29	0.04

It will be observed that the difference between the pH values of the dried and undried samples disappears if the time of extraction is prolonged to a week.

SUMMARY.

(1) The colorimetric method is unsuited to the examination of heavy, alkaline soils owing to the turbidity of the suspension.

(2) Where the nature of the suspension permits of colorimetric determinations being made, they agree with those obtained electrometrically: with the latter method practically identical results are obtained using soil-water mixtures or moderately clear extracts.

(3) No disturbing effect is likely to be introduced by amounts of nitrate up to 500 parts per million of soil.

(4) Owing to the effect on the pH of a soil suspension caused by varying the proportion of water and time of extraction, these conditions

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should be fixed for routine work. We have found 1 hour's extraction with 5 parts of water satisfactory.

(5) On account of the amphoteric or buffer nature of clay, soil shifts the reaction of acids and alkalis in the direction of neutrality.

(6) The effect of sodium salts on a soil is to displace aluminium and so reduce alkalinity: the residual soil after leaching is found to be more alkaline.

(7) The effect of drying alkaline soil is to cause the pH of the extract to be lower than that obtained from the undried soil. If however the time of extraction is prolonged, the differences disappear almost entirely.

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THE EFFICIENCY OF AMMONIUM SULPHATE AS A FERTILISER.

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DURING the course of a series of field experiments on the manuring of maize conducted at the Bahtim Experimental Station during the past few years, conditions have been worked out under which ammonium sulphate consistently gives results approaching to or equalling those obtained with nitrate of soda or nitrate of lime. While in the case of nitrate of soda it has been found that the application in two top dressings usually gives the best results, within reasonable limits the time of application, before or after sowing, is not so important as in the case of ammonium sulphate. It has been found that to secure the best results under our local conditions at Bahtim, this fertiliser should be applied as a top dressing some twenty days after sowing. It had usually been recommended, following R. Warington's¹ original advice for certain English conditions that this manure should be applied before sowing, in order to give time for nitrification to take place, it being generally assumed that this was a process necessitating at least a number of weeks. Under these conditions the existing Egyptian data indicate that nitrogen for nitrogen, ammonium sulphate has an efficiency of 90 to 95 per cent. when compared with nitrate of soda.

While the results obtained in our experiments are of purely local value as to their immediate application to field practice so that the best conditions for each individual Egyptian farm and system of maize cultivation will necessarily need to be worked out separately, the interpretation of the results should find a much wider application and may possibly be of service in the interpretation of the data available in other countries.

The conditions under which the results were obtained were as follows—the Egyptian maize crop takes up its nitrogen very rapidly, up to 45 kilos of nitrogen per acre being assimilated in 60 days.

¹ R. Warington, *Journ. Roy. Agric. Soc.*, 61, 300. 1900.

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Any nitrogenous manure must be readily available and in fact from Egyptian farmyard manure the maize crop is only able to take up nitrogen originally present in the form of nitrate or ammonia. Nitrification may, however, be exceedingly rapid, and in the laboratory experiments described below an ordinary dressing of ammonium sulphate is seen to be completely nitrified in the course of a few days, the average rate of disappearance of the ammonia being about 13 parts of nitrogen per million per day.

A set of bottle experiments was made up in July 1922, using the Bahtim soil on which the field experiments had been conducted. The moisture content of the soil was maintained at 22 per cent. while the storage temperature was about 30° C. Ammonium sulphate equal to approximately 100 parts of nitrogen per million of dry soil was added and determinations were made of nitrate and ammonia. The following table illustrates the rapidity with which the nitrification may take place under Egyptian conditions.

Table I. *Nitrification of ammonium sulphate in an Egyptian soil, at 22 per cent. moisture content and 30° C.*

Day	Nitrogen per million of dry soil.			
	Original soil		Soil with ammonium sulphate	
	Nitrate	Ammonia	Nitrate	Ammonia
0	48	Nil	44	100
3	50	"	75	57
7	53	"	114	12
14	57	"	147	Nil

From the data it is impossible, in view of the known rapid fluctuations of the nitrate content in soil, to determine whether there has been any loss of nitrogen during the process of nitrification, but it is probably safe to follow R. Warington's opinion in this matter and accept the transformation as quantitative, particularly in view of the evidence furnished by the field experiments. As the Egyptian soil is distinctly alkaline (pH about 8.0) it seemed probable that the early application of ammonium sulphate to a soil before the germination of the seed, under the intense sunshine and rapid evaporation of the Egyptian summer and with a prevailing breeze, would be followed by a liberation and subsequent dispersal of ammonia. When the crop was already established and several centimetres high the conditions would be much less severe. The naturally high absorptive power of the soil would help

to counterbalance this effect. Such a source of loss had already been indicated in the case of Egyptian farmyard manure with soil as an absorbent, stored in a current of air¹. R. Warington attributed some of the Rothamsted results to the liberation of ammonia from the manure by the calcium carbonate in the soil and this was later confirmed by A. D. Hall and N. H. J. Miller² who found unusually large amounts of ammonia in the atmosphere above fields that had recently been manured with ammonium sulphate.

Sir E. J. Russell and E. H. Richards³ also suggest agricultural soils as a source of the high ammonia content of summer rain. As the loss in effectiveness is a matter of 5 to 10 per cent. only, this liberation of ammonia by the soil may account for the results of many field experiments so far observed. This liberation of ammonia need no longer be attributed to any particular reagent in the soil, but as will be seen below, can readily be related to the reaction of the soil expressed in terms of the hydrogen-ion concentration.

EXPERIMENTAL.

The experimental work may be divided into two parts, firstly, the field experiments carried out with the collaboration of Mr Hassan Nazmy, and secondly laboratory tests on the liberation of ammonia from the soil.

In the field experiments the time of application of the ammonium sulphate varied as follows: seven days before sowing, the day before sowing, at the time of sowing and some twenty days after when the crop needed its first irrigation. When applied seven days before, the fertiliser was not in intimate contact with the soil, which was quite dry at the surface, and was not watered in until the time of seed sowing. The maximum yield is obtained when the manure is applied as a top dressing and under these conditions as will be seen from the data of 1921 when increasing amounts were employed, the data fit precisely the same Mitscherlich curve as is obtained with nitrate of soda, even agreeing in the breakdown which takes place in our experiments when the quantity of nitrogen added exceeds 45 kilos per acre, associated with the introduction of a new limiting factor.

In the experiments of 1921 and 1922, the manures were carefully sampled at the time of application and the chemical composition controlled.

¹ J. A. Prescott, *Sultanic Agricultural Society, Egypt, Bulletin* No. 8.

² N. H. J. Miller, *Journ. Agric. Sci.*, **4**, 56. 1911.

³ *Journ. Agric. Sci.*, **9**, 309. 1919.

Table II. *Manuring Experiment with Maize, 1920.*

Yields per acre. Averages of 4 plots of 1/20 acre.

Treatment	Stalks kilos	Dry ears kilos	Bushels
1. Nitrate of soda (150 kilos) applied in two top dressings	2920	1548	46.0
2. Sulphate of ammonia (115 kilos) applied seven days before sowing	2600	1290	38.7
3. Sulphate of ammonia (115 kilos) applied one day before sowing	2460	1156	34.4
4. Sulphate of ammonia (115 kilos) applied at the time of sowing	2520	1188	35.3
5. Sulphate of ammonia (115 kilos) applied as a single top dressing	2940	1566	46.6

Table III. *Manuring Experiment with Maize, 1922.*

Yields per acre. Averages of 4 plots of 1/40 acre.

Treatment	Stalks kilos	Dry ears kilos	Bushels
1. Sulphate of ammonia (150 kilos) applied as a single top dressing	4750	1860	55.2
2. Sulphate of ammonia (150 kilos) applied seven days before sowing	4790	1650	49.1
3. Sulphate of ammonia (150 kilos) applied 1 day before sowing	5170	1660	49.3
4. Nitrate of soda (equivalent) applied at time of sowing	4730	1760	52.3

In the case of the experiment of 1920, the method of application of the nitrate of soda is the best so far worked out for the local conditions.

The experiment of 1922, where the nitrate is added at the time of sowing, emphasizes the fact that nitrate of soda is not so much subject to the source of loss as is sulphate of ammonia.

Table IV. *Yields of maize obtained by manuring with increasing dressings of nitrate of soda and sulphate of ammonia, Bahtim 1921.*

	Nitrogen added in manure kilos per acre	Dry ears kilos per acre	Bushels
Nitrate of soda			
0	0	1610	47.9
100	15.1	2276	67.5
150	22.7	2410	71.9
200	30.3	2730	81.7
300	45.4	2936	87.1
400	60.5	2910	86.6
Sulphate of ammonia			
0	0	1610	47.9
75	15.3	2304	68.7
150	30.7	2670	79.3
200	40.9	2950	88.1
250	51.1	2930	87.1
300	61.3	3050	90.2

In this experiment, the two fertilisers were added in the same way, that is, as a single top dressing at the first irrigation after seed sowing.

The above results represent the average of duplicate plots each of 1/20 acre. They will be seen from Fig. 1 to lie on the same curve represented up to 45 kilos of nitrogen by the Mitscherlich equation,

$$\log (A - y) = K - Cx,$$

where $A = 3800$ kilos, $K = 3.342$ kilos, $C = 0.0096$ kilos.

The evolution of ammonia from soil treated with ammonium sulphate.

During the few days before which nitrification is complete it has been pointed out that liberation of ammonia may occur owing to alkaline character of the Egyptian soil. This was confirmed in several ways.

In the first experiment 100 gms. of Bahtim soil at 22 per cent. moisture content and containing 100 parts per million of ammonia

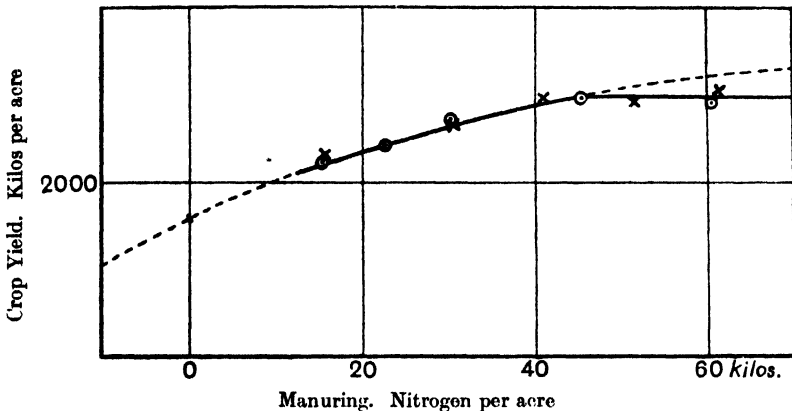


Fig. 1. Showing equivalence of nitrate of soda and sulphate of ammonia under the conditions of the Bahtim experiment, when applied as a top dressing to the crop. Rings represent yields with nitrate of soda, crosses represent yields with sulphate of ammonia. The broken line shows the extension of the Mitscherlich curve.

nitrogen were placed directly into the Matthews soil ammonia apparatus, but without the addition of any alkaline solution or other liquid. After 6 hours' aeration, 6 per cent. of the ammonia was found to have been blown over into the standard acid, while after 24 hours 17 per cent. of the original ammonia was found to have been removed. There was in addition a marked drying of the soil.

In a second experiment, to the surface of a pot 40 cm. in diameter and containing 40 kilos of soil were added 8 gm. of ammonium sulphate which was then watered in. A dish containing sulphuric acid was then placed on the surface of the soil and covered with a bell jar 30 cm. in diameter. After seven days the acid was removed and the ammonia

fixed by it was determined in the usual way. A pot to which no ammonium sulphate had been added gave off under these conditions 0.001 gm. of nitrogen while the manured pot gave off 0.0331 gm. of nitrogen representing 3.5 per cent. of the nitrogen added in the ammonium sulphate.

The next step was to determine the relationship of the soil reaction to its power of liberating ammonia from ammonium salts. This was done in two ways. In one case 25 gm. of soil were placed in the Matthews soil-ammonia apparatus together with 10 c.c. of an ammonium sulphate solution containing 0.0192 gm. of nitrogen and 50 c.c. of water containing varying amounts of decinormal acid or alkali. After three hours aeration the ammonia liberated was determined as well as the pH of the residual soil mixture. The following table gives the results of this experiment.

Table V. *Liberation of ammonia from soil at different hydrogen-ion concentrations by three hours' aeration.*

pH of residual soil mixture	Nitrogen liberated % of originally present
7.2	3
7.3	3
7.6	3
8.0	5
8.2	8
8.3*	8
8.6	11
8.8	18
8.9	34
9.1	47

* Untreated soil.

This was further confirmed by aerating under similar conditions, boric acid buffer solutions containing a known amount of ammonium sulphate.

Table VI. *Liberation of ammonia from ammonium sulphate by buffer solutions of varying alkalinity.*

110 c.c. buffer solution containing 0.0212 gm. N.

Final pH of buffer solution	Nitrogen removed after 3 hours' aeration % of original added
7.6	2.7
8.1	9.4
8.2	10.4
8.4	22.6
8.6	34.3
9.0	45.9
9.3	62.8

Further confirmation was obtained by using naturally occurring Egyptian soils of varying alkalinity.

SUMMARY.

Field experiments with maize at the Bahtim Experimental Station and laboratory tests indicate that the lower efficiency of ammonium sulphate as compared with nitrate of soda is due principally under these special conditions to the liberation of ammonia from the fertiliser in contact with an alkaline soil. The rate of this liberation is a function of the aeration and of the soil reaction.

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THE MAXIMUM WATER-RETAINING CAPACITY OF COLLOIDAL SOILS; THE INTERPRETATION OF THIS AND OF CERTAIN OTHER SOIL MOISTURE CONSTANTS.

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SECTION I. INTRODUCTION.

THE maximum water-retaining capacity of a soil may be defined as the quantity of water, measured as a percentage of the mass of oven-dry material, that the soil can retain after it has been thoroughly wetted and then allowed to drain freely. It is generally estimated in the laboratory by Hilgard's method (1893)¹. The air-dried sifted soil is packed by jarring into a small perforated cylindrical brass box which is then placed in a vessel containing water, so that the bottom layer of the soil is in contact with the liquid surface. After standing an hour, the cylinder is removed, surplus water wiped away, and the whole weighed. The cylinder and contents are then dried to constant mass in an air-oven at 110° C. The weighings are corrected for the mass of the cylinder and that of the filter paper employed to cover the sieve. From the results, the maximum water-retaining capacity may directly be calculated.

The magnitude of the maximum retentivity constant, as estimated by this method, obviously depends on the colloid content of the soil (imbibition capacity), on the degree of packing, and on the extent of drainage allowed. By use of a shallow container, it is believed that undue stretching of the water-films which surround the component particles of the soil, due to gravitational pull, is largely eliminated.

Briggs and Shantz² have derived an empirical formula connecting the maximum water-retaining capacity (M) with the hygroscopic coefficient (H) by considerations based on Hilgard's work, and on the results of their own examination of certain sand and silt soils. The Briggs-Shantz formula is $M = 4.3H + 21$. The accuracy of this equation, in its generalised application to soils, has been doubted by Alway and

¹ Hilgard, *Soils*, 1918, p. 209.

² U.S. Bur. Plant Indus., *Bul.* 230. 1912.

Clark¹ (1916). These authorities noted considerable divergencies between the calculated and the determined maximum water-retaining capacities for Nebraska loess soils, and for Californian soils of diverse types that had previously been investigated by Loughridge². In the case of the former, divergencies varying between 4.3 and - 16.8 were recorded, and in the latter, 26.8 and - 28.4. The data presented, however, do not include exact specifications of the soil types considered, nor is any explanation offered to account for the irregularities. Alway and McDole, in a later paper³, nevertheless admit that, in the case of soils with hygroscopic coefficients lying between 3 and 14, water retentiveness bears a rather simple relation to the hygroscopic coefficient. In coarser soils, however, the ratio appears to be less simple.

Wilsdon⁴, in 1921, offered a physical interpretation of the constants in the Briggs-Shantz equation. By mathematical reasoning, he first demonstrated that ideal sands have identical maximum water-retaining capacities, no matter what size their particles, provided they are packed to the same extent. At maximum (hexagonal) packing, the value deduced for the constant is 23.46, which is remarkably near the figure 21 that occurs in the Briggs-Shantz equation. Secondly, Wilsdon suggested that the factor $4.3H$ in the Briggs-Shantz formula represents the total colloiddally-imbibed (total bound) water present in a soil that contains colloidal matter. He adduces experimental evidence to support the theory that soil colloids possess a reticulate structure, and that the water content of the fully saturated colloids exists in two phases, namely "gel" water, which is adsorbed in the walls of the reticulum, and "vesicular" water, which fills the internal pores or vesicles. Furthermore, he showed that gel water corresponds to the water content of a soil at the hygroscopic coefficient stage. Wilsdon found in the case of a silt-loam from Lyallpur, India, that the ratio of total bound water (gel plus vesicular water) to gel water is 4.73. This ratio he termed the "vesicular coefficient," and its approximation to the figure 4.3 in the Briggs-Shantz equation led to the generalisation already mentioned. It should be noted, however, that Wilsdon was aware that the specific character of the soil colloid might cause variations in the vesicular coefficient, and in consequence, might affect the general applicability of the Briggs-Shantz formula as interpreted by him, to soils of diverse geological origins.

¹ *Journ. Agric. Research*, **7**, 345. 1916.

² *Calif. Agric. Expt. Sta., Rpt.*, 1892-94, p. 70.

³ *Journ. Agric. Research*, **9**, 27. 1917.

⁴ *Mem. Dept. Ag. India, Chem. Series*, **6**, 3. 171. 1921.

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The writer¹, in a recent paper, has attempted to compare the vesicular coefficients of the colloidal material that characterises certain West Indian soils of different geological types. The method employed to measure total bound water differs from that used by Wilsdon. It is mainly based on the theoretical argument that, when the colloidal material in a soil is fully saturated with water, external adhesion then, and only then, becomes manifest. Hence the moisture content of a colloidal soil at the onset of external adhesion (the point of "stickiness") may be taken as a measure of the total imbibition capacity of the colloid content. The results presented indicate that the vesicular coefficient varies markedly for soils of different geological types. The limits obtained were 4.68 and 2.37; the lowest value being exhibited in a red lateritic soil from Barbados.

In view of the simplicity of Wilsdon's interpretation of the Briggs-Shantz constants, it was thought desirable to estimate the maximum water-retaining capacities of the West Indian soils employed by the writer in the previous investigation, and to compare the results with values calculated from the empirical formula of Briggs-Shantz, and from that suggested by Wilsdon's researches.

SECTION 2. EXPERIMENTAL.

The soil samples examined belong to types that have already been described in the previous paper, namely:

Type 1. Sandy soils, loams, and clay soils derived from fragmental volcanic rocks of andesitic relationship (Montserrat, Antigua, Barbados).

Type 2. Clay soils, sedentary on calcario-siliceous sediments (Antigua).

Type 3. Clay soils, sedentary on siliceous non-calcareous sediments, (Antigua).

Type 4. Red lateritic soils.

(a) Clay soils derived by lateritisation from andesite (Dominica).

(b) Residual clay soils overlying coral limestone containing intercalated andesitic ash (Barbuda, Barbados).

Type 5. Highly humic soils.

(a) Black calcareous soil, 8.1 per cent. humus (Barbuda).

(b) Cacao-pod mulch, 52.1 per cent. humus (Dominica).

Hygroscopic coefficients were estimated by Hilgard's method as modified by Mitscherlich and by Beaumont². At least five replicate determinations were carried out on each soil sample, using different humidifiers.

¹ Hardy, F., *Journ. Agric. Sci.*, **13**, 243. 1923.

² Cornell Univ. *Ag. Expt. Sta., Mem.* 21, p. 497. 1919.

Table I. *Comparison of determined values of maximum water-retaining capacity with calculated values derived from two formulae, for soils of different geological types.*

Soil type	1	2	3	4	5	6	7	8	9
	Humus content (approximate)	Hygroscopic coefficient (H)	Moisture content at point of stickiness (P)	Maximum water-retaining capacity (M)	Vesicular coefficient (P) (H)	Calculated retaining capacity from formulae (4.3H + 21) (P + 23.5) Briggs-Shantz (A) (B)			
Type 1 M 11	2.3	2.0	17.7	29.8	8.8	29.6	41.2	0.2	-11.4
M 13	2.5	4.4	25.2	44.2	5.7	39.9	48.7	4.3	-4.5
M 9	2.0	5.1	26.4	45.0	5.1	42.9	49.9	2.1	-4.9
M 6	2.1	6.8	33.3	53.6	4.9	50.2	56.8	3.4	-3.2
M 4	5.2	7.1	35.4	60.1	4.9	51.5	58.9	8.6	1.2
M 7	5.1	8.5	37.2	67.9	4.4	57.5	60.7	10.4	7.2
Bdl	1.6	7.2	33.7	64.2	4.7	51.9	57.2	12.3	7.0
BaS	0.9	8.1	37.5	65.1	4.6	55.8	61.0	9.3	4.1
Mean probable errors*	—	±0.06	±0.13	±0.55	—	—	—	—	—
Type 2 A Th	3.0	11.5	45.1	78.6	3.9	70.4	68.6	8.2	10.0
A 38	1.2	11.9	42.0	81.5	3.5	72.2	65.5	9.3	16.0
A 6	1.5	12.3	45.6	85.0	3.7	73.9	69.1	11.1	15.9
A 10	1.0	12.7	49.1	90.3	3.9	75.6	72.6	4.7	17.7
Mean probable errors*	—	±0.20	±0.36	±0.85	—	—	—	—	—
Type 3 A 41	1.1	13.4	44.1	91.6	3.3	78.6	67.6	13.0	24.0
A 13	1.6	13.5	49.8	94.1	3.6	79.0	73.3	15.1	20.8
A 46	1.3	14.1	46.9	101.2	3.3	81.6	70.4	19.6	30.8
Mean probable errors*	—	±0.25	±0.50	±1.20	—	—	—	—	—
Type 4 (a) D 1	0.7	15.5	54.5	76.8	3.5	87.6	78.0	-10.8	-1.2
D 2	0.9	17.8	59.3	85.3	3.3	97.5	82.8	-12.2	2.5
(b) BaR	2.8	16.6	57.2	82.7	3.4	92.4	80.7	-9.7	2.0
BaR	0.5	20.6	48.8	75.1	2.4	109.6	72.3	-34.5	2.8
Mean probable errors*	—	±0.12	±0.15	±0.65	—	—	—	—	—
Type 5 (a) BaB	8.1	16.4	61.0	83.5	3.7	91.5	84.5	-8.0	-1.0
(b) Cac	52.1	18.7	209.6	254.9	11.2	101.4	233.1	153.5	21.8
Mean probable errors*	—	±0.16	±0.17	±0.80	—	—	—	—	—

* Calculated from the formula $E_m = \pm 0.67 \sqrt{\frac{d^2}{n(n-1)}}$ applied to the results of the replicates of each determination.

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Moisture contents at the point of stickiness were determined by drying at 110° C. material that had been worked up with water to the stage when the plastic mass began to adhere to the hands. Five replicates of each were run, separate amounts of soil being kneaded for each.

Maximum water-retaining capacities were estimated by Hilgard's method, using perforated cylindrical brass boxes of volume 22 c.c. The soil samples were passed through a 1 mm. sieve, and packed into the cylinders by mechanical jarring. Five replicates of each were run.

Humus contents were estimated by a wet combustion method, using chromic acid. Humus = organic carbon \times 1.724.

The data obtained, with corresponding probable errors, are presented in Table I.

In order to check the results, the clay fractions of samples representative of the first four soil types were isolated by conventional methods of elutriation and precipitation, and values for the three moisture constants re-estimated with this material. The results are set out in Table II. The soils before use were ground so as to pass a sieve of 100 meshes to the inch.

Table II. *Results obtained with clay fractions.*

Soil Type		Hygroscopic coefficient* (H)	Moisture content at point of stickiness† (P)	Maximum water-retaining capacity† (M)	Vesicular coefficient (I') (H)	Calculated retaining capacity		Difference between detd. and calcd. values	
						(4.3H + 21) (A)	(P + 23.5) (B)	(A)	(I)
		1	2	3	4	5	6	7	8
Type 1	Bdl	13.1	61.8	91.5	4.72	77.3	85.3	14.2	6.2
	BsS	14.5	69.1	102.3	4.76	83.3	92.6	19.0	9.7
Type 2	A C	21.0	78.4	106.8	3.73	111.3	101.9	- 4.5	4.9
Type 3	A D	22.2	80.4	110.0	3.62	116.4	103.9	- 6.4	6.1
Type 4	(a) D 2	19.1	63.2	91.3	3.31	103.1	86.7	- 11.8	4.6
	(b) BsR	23.2	55.7	84.6	2.40	120.7	79.2	- 36.1	5.1

* Means of five replicates. Mean probable error for H = \pm 0.31.

† Means of duplicates.

Finally, samples of the four main soil types were examined according to the methods recommended in a recent paper by Keen and Raczkowski¹. Values obtained for the physical constants are given in Table III. They may serve further to characterise the West Indian soils studied in this and in the previous investigation.

Table III. *Physical constants of soils, determined by the methods of Keen and Raczkowski, on material passing a 100-mesh to the inch sieve, and packed into perforated brass boxes.*

		Apparent specific gravity of air-dry soil	Water absorbed per 100 grs. of oven-dry material	Pore-space of air-dry soil as packed	True specific gravity of oven-dry material	Volume expansion per 100 cc. of oven-dry material	(For comparison) Per cent. volume expansion from shrinkage experiments*
		1	2	3	4	5	6
Type 1	Bdl	1.11	82.4	64.8	2.25	33.7	17.2
	BsS	1.12	69.8	62.1	2.41	18.9	18.6
Type 2†	A C	1.08	118.8	70.3	2.12	61.3	23.8
Type 3†	A D	1.11	122.7	70.6	2.10	66.9	24.3
Type 4	(a) D 2	1.04	89.0	66.5	2.27	23.3	31.7
	(b) BsR	1.02	85.3	66.4	2.35	17.2	20.3

The values of the Keen-Raczkowski constants are the means of duplicate determinations.

* Reproduced from Table III, column 6, of the writer's previous article, "The physical significance of the shrinkage coefficient of clays and soils," *Journ. Agric. Sci.*, **13**, 243. 1923.

† Bulk samples.

SECTION 3. DISCUSSION OF THE EXPERIMENTAL DATA.

(A) THE BRIGGS-SHANTZ RELATIONSHIP.

(a) *Soils of Types 1, 2, and 3.*

The figures for maximum water-retaining capacity (Table I, column 6), as calculated from estimated hygroscopic coefficients on the Briggs-Shantz formula, show progressively increasing divergencies from the experimentally determined values in the cases of soils belonging to Types 1, 2, and 3 (column 8), as the hygroscopic coefficients increase. For silty soils of low hygroscopic coefficients (Montserrat soils, M 11, 13, 9, and 6), the divergencies are significantly small enough to be almost negligible. Evidently the Briggs-Shantz formula applies quite accurately to such soils.

As the magnitude of the hygroscopic coefficient increases above 7.0, for Types 1, 2, and 3, the differences between estimated and calculated values for the maximum water-retaining capacity become considerable. This probably is due to three main causes, namely, (i) the difficulty of obtaining initial maximum packing in the dry colloidal soils¹, (ii) the tendency towards a complete filling up with water of the interstitial pore spaces of the soil as the process of absorption proceeds², and (iii) the

¹ The pore space of the air-dry soils, passed through a 1 mm. sieve, and packed into perforated brass boxes, was found to vary between 55 and 65 per cent. The theoretical pore space for particles of a given diameter in maximum packing is 26 per cent.

² In practice, it is impossible to obtain only film water between the soil particles. Two different definitions for the maximum water retentivity constant have therefore arisen;

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swelling of the colloid-coated particles, consequent on imbibition, which, by progressively "loosening up" the soil, increases the volume of the pore spaces, and therefore also the quantity of water drawn into them by capillary forces.

The first of these factors tends to diminish the amount of free water held as films between the soil particles at their points of contact, since the number of contacts is less, the less the extent of packing. The second and third factors, however, act in the opposite direction, tending to increase the quantity of free water in the soil, and thus to cause the estimated values for the maximum retentivity constant to be in considerable excess of the calculated values. This effect becomes more pronounced the greater the colloid content of the soil.

The data in Table III, column 5, indicate the extent to which swelling occurs in the moistened packed soils. It is relatively very high in soils representative of Types 2 and 3.

The last two factors enumerated are believed mainly to account for the discrepancies between the values for the maximum retentivity constant as calculated from the Briggs-Shantz formula and as determined experimentally, for highly colloidal soils of Types 1, 2, and 3, and to render the applicability of the Briggs-Shantz formula to such soils entirely irrelevant.

(b) *Soils of Type 4 (Lateritic soils).*

Contrary to the case of soils of Types 1, 2, and 3, the experimentally determined maximum water-retaining capacities of the lateritic soils are in considerable deficit of the values derived by calculation from the Briggs-Shantz equation. Reference to Table III, column 5, shows that the lateritic soils examined exhibit remarkably low volume expansion on moistening¹, notwithstanding the fact that they are highly colloidal. This is probably a major reason accounting for the result stated.

certain writers (*e.g.* Hilgard) define the constant as the quantity of water that a soil can hold when the pore spaces are *completely filled* with water; others (*e.g.* Wilsdon), as the quantity of water held when free liquid occurs only as surface films.

¹ A somewhat similar result was obtained in connection with the determination of shrinkage coefficients (see Table III, column 6). The numerical results obtained are not, of course, comparable with those obtained in the retentivity experiments, since the state of the material on which volume expansion was measured, differed in the two cases. The phenomena of volume expansion of soils, both under natural and artificial conditions, are being further investigated.

Another factor which tends in the same direction, namely to minimise water absorption by the air-dry packed soil, is the low vesicular coefficient possessed by the colloidal material that characterises typical lateritic soils (see Table I, column 5). It is not correct to use the Briggs-Shantz factor 4.3 in calculating total bound water in all cases, for soils of different geological types appear to contain specifically different colloids.

(c) *Soils of Type 5 (Humic soils).*

In the case of the second of the humic soil samples examined (Cac), the divergency between the determined and the calculated values for the maximum water-retaining capacity is very great, and in all probability is accounted for, as in the case of the highly colloidal soils of Types 2 and 3, by the very great volume expansion exhibited by the colloidal material that characterises it. Humus appears to contain a colloid of structure specifically different from that of the commoner inorganic soil colloids¹.

(B) THE SUGGESTED NEW RELATIONSHIP ($P + 23.5$).

In this formula (Table I, column 7), total colloiddally imbibed water is measured by the moisture content at the point of stickiness (P), and film water by Wilsdon's constant, 23.5.

(1) In the case of soils of low colloid content (sandy and silty soils) it was pointed out in the previous paper that the moisture content at the point of stickiness is not an exact measure of total bound water, but is in considerable excess of it. Hence the calculated values for the maximum water-retaining capacity of such soils are too high; this is clearly shown in Table I by the data for the Montserrat soils, M 11, 13, 9, and 6.

(2) As the magnitude of the hygroscopic coefficient increases above 7.0, the differences between experimentally determined and calculated values for the maximum retentivity constant again, as in the case of the Briggs-Shantz relationship, become considerable (Table I, column 9), and are due to causes already discussed.

(3) Lateritic soils (Type 4), of relatively low volume expansion, yield values for the determined and the calculated maximum retentivity constant which are approximately identical. The proposed formula therefore seems to apply quite closely to these soils.

(4) Humic soils (Type 5) call for no further comment.

¹ The reader is referred to Wo. Ostwald, *Theor. and Applied Colloid Chem.*, 1917, p. 152, for references to literature on the subject of the structure of humus colloids, and to Bancroft, *Applied Colloid Chem.*, 1921, p. 76, for an account of the colloid science of cellulose.

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SECTION 4. THE INTERPRETATION OF CERTAIN OTHER SOIL MOISTURE CONSTANTS.

1. THE WILTING COEFFICIENT.

This constant, first proposed by Briggs and Shantz¹ (1912), is a measure of the moisture residue in a soil at the stage when the leaves of plants that are growing in it first undergo permanent reduction in their water content. According to the results of recent researches, its magnitude is apparently independent of the kind of plant grown².

Briggs and Shantz have suggested a formula connecting the wilting coefficient (W) with the hygroscopic coefficient (H), thus— $W = 1.47H$. According to Wilsdon, the total bound (colloidally-imbibed) water in a soil may be represented by $4.3H$, of which $3.3H$ (approximately 70 per cent.) represents the vesicular water of the soil colloids. Hence, at the wilting point, a soil contains $\frac{1.47H}{4.30H}$ (approximately 34 per cent.) of its original total bound water, so that 66 per cent. of the bound water has been removed by the plant. Since the quantity of the vesicular water is approximately 77 per cent. $\left(\frac{3.3H}{4.3H} \times 100\right)$ of the total bound water, this means that, at the wilting point, 86 per cent. of the vesicular water of the soil colloids has been removed. Evidently the forces of imbibition of plant roots are not of sufficiently great magnitude to deplete the soil colloids of their absorbed water below this point.

Recently, Mason³ has estimated the ratio of the moisture content at the point of stickiness to the wilting coefficient for a limited series of West Indian soils of different geological origins. For two Barbados red soils, the ratio is 1.45; for a black soil, 1.62; for a grey calcareous soil, 1.59; and for certain artificial soils consisting of mixtures of black soil and sand, from 1.76 to 2.05. These figures show divergencies between themselves, and from the figure $2.92 \left(\frac{4.3H}{1.47H}\right)$ derived from the Briggs-Shantz formulae. The divergencies are probably partly due to the specific nature of the colloidal material that characterises the three geological soil types represented in Mason's series⁴.

¹ *U.S. Bur. Plant Indus., Bul. 230.* 1912.

² For a discussion of the significance of the wilting coefficient, see Blackman, *Journ. Ecology*, 2, 43. 1914; also Mason, *West Ind. Bul.* 19, 138. 1922. The relationship between this, as well as that of other soil moisture constants, and vapour pressure gradients in soils is fully considered by Thomas, *Soil Science*, 11, 409. 1921.

³ *West Ind. Bul.* 19, 153. 1922.

⁴ Mason, however, considers the divergencies not to be significant.

2. THE MOISTURE EQUIVALENT.

This soil constant represents the moisture residue in a soil that has been subjected to a centrifugal force of magnitude 3000 times that due to gravity¹. It was first formulated in an attempt to subdivide the soil water on a physical basis, and was supposed to mark the stage when most of the water had been removed from the interstitial pore spaces of a soil². The Briggs-Shantz equation connecting the moisture equivalent (E) with the hygroscopic coefficient (H) is $E = 2.7H^3$. It follows by comparisons between this formula and others previously considered, that the water content of soil colloids at the moisture equivalent stage is lower than that which is requisite for complete imbibition (for $2.7H$ is less than $4.3H$), but is higher than either the hygroscopic coefficient (H), or the wilting coefficient ($1.47H$). It is easily shown by calculation to represent a loss of approximately 37 per cent. of the total bound water, or 47 per cent. of the vesicular water, as brought about by centrifuging.

3. THE CRITICAL MOISTURE CONTENT.

Cameron and Gallagher define the critical moisture content of a soil as "the point where the effective film forces are just sufficient to cause changes in the internal soil arrangement⁴." At this point it appears to be most easily possible to impress a crumb structure on a soil, for cohesion and penetrability apparently then have their highest values⁵. The critical moisture content may thus be assumed to be coincident with the moisture content at true maximum plasticity, for film tension is also believed to be a maximum at this point. Cameron and Gallagher found, moreover, that the critical moisture content of various soils examined by them approximated to the moisture equivalent constant⁶. This fact gives added significance to the last-named constant, and identifies it, in theory, with the moisture content at true maximum plasticity. It has already been shown that the water content of a soil

¹ Briggs and McLane, *U.S. Bur. Soils, Bul. 45*. 1907.

² See Russell, *Soil Conditions and Plant Growth*, 1921, pp. 218-27, for a summary of the main facts connected with the water supply of the soil. Also Keen, *Journ. Agric. Sci.*, **10**, 60-64. 1920.

³ *U.S. Bur. Plant Indus., Bul. 230*. 1912.

⁴ *U.S. Bur. Soils, Bul. 50*, p. 50. 1908.

⁵ *Ibid.* p. 52.

⁶ Davis (*Journ. Ind. Engin. Chem.*, **6**, 1008. 1914), has adduced evidence to show that the critical moisture content of a soil is also numerically equal to the *minimum* water-retaining capacity, i.e. to the moisture content at the upper end of a column of soil that has been allowed to take up moisture by vertical capillarity from a reservoir.

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at the moisture equivalent stage is approximately equal to 63 per cent. ($= 100 - 37$) of the total water which the soil colloids are capable of imbibing. Hence, since maximum plasticity is apparently also attained at the moisture equivalent stage, we have some indication of the degree of saturation of the soil colloids when film tension is at its maximum. It must be borne in mind, however, that these results are, at best, merely approximations, being based on empirical formulae applied to a particular soil type. One might not be justified in pursuing them to their ultimate conclusions. They need modification when applied to soils containing specifically different colloidal material.

SUMMARY AND CONCLUSIONS.

1. The paper describes an investigation into the applicability of the Briggs-Shantz relationship connecting maximum water-retaining capacity (M) with the hygroscopic coefficient (H), i.e. $M = 4.3H + 21$, to soils containing appreciable amounts of colloidal matter of different specific nature.

2. The soils employed are the same as those used in a previous investigation into the significance of the shrinkage coefficient, and belong to diverse geological types represented in the British West Indies.

3. The results indicate that the Briggs-Shantz equation, whilst generally applicable to soils whose colloidal properties are not marked, yields values for the calculated maximum retentivity constant that are in considerable deficit of the experimentally determined values when applied to highly colloidal soils containing *siliceous* colloids. This result is believed to be mainly due to the marked volume expansion exhibited by these soils when wetted.

4. In the case of red *lateritic* soils, in which the colloid content is composed mainly of alumina hydrogel and ferric oxide hydrogel, the calculated values for the maximum retentivity constant, on the contrary, are in excess of the estimated values. These soils, though highly colloidal, exhibit remarkably low volume expansion on wetting.

5. Wilsdon's interpretation of the constants in the Briggs-Shantz equation is discussed, and applied to the experimental data obtained. Wilsdon has suggested that the factor $4.3H$ represents the total bound water imbibed into the colloidal material of soils packed into perforated boxes such as are used in determinations of the maximum retentivity constant. The figure 4.3 is termed the "vesicular coefficient" of the colloidal material. In the *siliceous* West Indian soils examined, the vesicular coefficient appears to vary between 4.9 and 3.3 , with a mean

value of 4.2; whereas, for red lateritic soils, it varies between 3.5 and 2.4, the lowest figure being given by the most typical of these.

6. The low vesicular coefficient of the colloidal material that characterises the lateritic soils is believed partly to account for the discrepancy between the calculated and the estimated values for the maximum retentivity constant mentioned in paragraph 4.

7. A new formula connecting maximum water-retaining capacity with total bound water and with free interstitial film water, is next tested. In this formula, total bound water is represented by the moisture content of a soil at the point of stickiness, it being believed that, at this stage, the soil colloids are completely saturated with water. The results obtained indicate that this formula also fails to yield concordance with experimental data, except in the case of lateritic soils, for which it seems to apply quite closely.

8. The main reason for failure in the application of the new formula to colloidal soils containing *siliceous* colloids, again appears to be the marked volume expansion which these soils exhibit when wetted.

9. Interesting results, in general agreement with those obtained with soils containing inorganic colloids, were yielded by two highly *humic* soils.

10. The bearing of the theories and results discussed on the significance of other soil moisture constants, namely, the wilting coefficient, the moisture equivalent, and the critical moisture content, is examined. The importance of recognising specificity in soil colloidal material is again urged.

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ON THE VIBRATION METHOD OF OBTAINING A SUSPENSION OF THE BACTERIA IN A SOIL SAMPLE, DEVELOPED BY C. L. WHITTLES.

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As has long been realised by soil bacteriologists, the present plating technique used in estimating bacterial numbers in soil suffers from the lack of a really efficient means of disintegrating the soil, so as to produce an even suspension of the organisms in the diluting fluid. As a consequence of this, although we are able, by careful standardisation of the shaking and dilution, to compare the bacterial numbers in two or more samples of the same soil type, the figures obtained are only relative, and do not give an estimate of the total bacterial numbers of the soil.

Mr C. L. Whittles (*Journ. Agric. Sci.* **13**, 18) has made an attempt to overcome this defect by means of an apparatus in which the soil suspension, instead of being shaken, is subjected to high frequency vibration. Plate counts of this vibrated suspension gave enormously high bacterial numbers as compared with counts of the same soil made by shaking. In one case the mean number of colonies developing on platings of a $1:10^{11}$ dilution was 276, giving an estimate of 27 billion bacteria per gram of soil. In another case 10 billion bacteria per gram were obtained. If the mean volume of a bacterial cell be taken as one cubic micron, a simple calculation shows that 27 billion bacteria will have a volume of 27 c.c. which is greatly in excess of the volume of soil from which the count was made. The figures obtained are thus clearly faulty and indicate that the technique, in its present state of development, contains defects that render it valueless for the purpose of bacterial analysis. It would seem that, in such an apparatus as is used, the difficulty of adequate sterilisation is very great and may not have been overcome.

To establish the validity of bacterial counts in soil, it is clearly necessary that concordant results should be obtained in a number of parallel counts from a soil sample. The few plate counts from vibrated soil given in the present paper, are on the other hand extremely discordant. The

author has also developed a technique for the direct counting of bacteria in stained preparations of the soil under the microscope. Without seeing these preparations it is impossible to say whether the previously unsurmounted difficulty of distinguishing between live bacteria, dead bacteria and soil particles has been overcome. A count obtained by this method gave 6,300,000,000 bacteria per gram. This figure, however, is apparently derived from a count of the bacteria in a single drop of soil suspension. It is therefore premature to discuss it until a number of parallel counts are recorded and the experimental error of the method determined.

The physical effects obtained with the vibrating apparatus seem to show that a high degree of disintegration of the soil suspension is effected. It is to be hoped that future work on this line may result in the development of a readily sterilisable apparatus by which a thoroughly disintegrated suspension of soil can be obtained, as this would be of great assistance to soil biologists.

The fact that physical factors, such as moisture content, can affect the ease with which soil particles can be dispersed by shaking, is one that needs serious consideration in connection with counting methods for soil microorganisms. The data at present at our disposal are insufficient to enable us to gauge the importance of these factors in influencing the accuracy of counting methods that depend on the formation of a soil suspension and its subsequent dilution. The effect of some of these factors on the formation of a soil suspension is at present being studied in the Physical Department at Rothamsted.

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THE SOIL-POINT METHOD FOR DIRECTLY ESTIMATING THE WATER-SUPPLYING POWER OF A SOIL IN THE FIELD.

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WORKERS in ecological problems have long felt the need of a reliable method for estimating the water-supplying power of soil *in situ*. This major factor in plant growth is the summation of many minor factors, of which not the least important is the *rate* at which a moist soil delivers water to the absorbing organs of plants rooted in it. Disturbing the soil in taking samples for physical examination in the laboratory obviously alters the arrangement of the component soil particles, and hence profoundly affects the internal dynamic water relationships. This fact furnishes a real objection to the employment of conventional soil moisture constants in comparing soils in the field.

The first attempt to elaborate a method for directly estimating the water-supplying power of soil was made in 1915 by Pulling and Livingston¹. A thistle-osmometer was used as an "artificial root." Difficulties in maintaining close contact between the absorbing membrane and the soil particles prevented, however, the wide employment of this instrument in field investigations. Subsequently, Livingston and Koketsu² in 1920 suggested another method in which small, dry, porous, porcelain cones ("soil-points") were used. In operation, a single cone is gently forced into the soil, and allowed to remain there for a definite period of time, generally two hours. The quantity of water absorbed during this period is then determined by weighing. The water-supplying power of the soil is expressed in hundredths of a gram of water absorbed by one soil-point in two hours. Experimental trials on soils of varying mechanical texture, but possessing the same degree of physiological humidity³, indicated that the method could be relied upon to furnish exact information as to water-supplying power.

¹ Carnegie Inst. Wash., Pub. 204, p. 49, 1915.

² *Soil Science*, 9, p. 469, 1920.

³ A series of soils, comprising various mixtures of sand, loam, and humus, were brought to the same state of physiological humidity by growing plants in them until their moisture contents had been reduced to a stage when the plants exhibited permanent wilting.

An ingenious modification of the soil-point method was examined by Mason¹ (1921). This investigator, at the suggestion of Dr Livingston, employed ordinary hard graphite writing pencils², sharpened in a rotary mechanical sharpener³. Their hard points enable the pencils easily to penetrate the soil; the varnish that covers the sides acts as a waterproof layer, preventing absorption except at the conical surface of the sharpened end. The mechanism of the transference of water from soil to soil-point is discussed, and the results of critically planned laboratory trials are presented by Mason in the paper cited. It was found that in examining soils of water content greater than 40 per cent., a time period of 30 minutes duration (using pencils in pairs) gives reliable results. For soils of water content lower than this, a longer period is required; three hours is recommended.

In order to test the soil-point method under field conditions, the writer has employed it in a soil moisture investigation on a sugar-cane estate in Antigua, B.W.I. It is with the hope that an account of the details of procedure, and a statement of the degree of reliability which may be expected, will be of use to British workers, that this paper is presented. No attempt will herein be made to discuss the particular problem in connection with which the method was employed, but attention confined entirely to a description of the method itself.

DETAILS OF PROCEDURE.

Experience proved that two complete determinations of the water-supplying power of the soil in neighbouring fields could be made by the soil-point method during one working day. In this particular instance, the estate where the investigation was carried out, is situated at a distance of two miles from the laboratory. Journeys to and from the fields were made on a bicycle.

Commencing at 7.30 a.m., one hundred pencils are sharpened; their points blunted by rubbing on sand paper, and adhering shavings removed with a cloth. The pencils are divided into two lots of fifty each. A single experiment necessitates the use of one of these lots, which is subdivided into five sets of ten pencils each, numbered 1, 2, ... 5. Pencils belonging to each of the numbered sets are given a distinctive mark. Pieces of coloured paper, attached by fish glue to the flat unsharpened ends, were found to answer the purpose admirably. The five sets of pencils are

¹ *West Ind. Bull.* 19, p. 137, 1922.

² Koh-i-noor pencils, 4H, Hardtmuth, were used.

³ "Chicago" sharpener, Automatic Pencil Sharpener Co., Chicago, U.S.A.

placed in five celluloid cases¹ bearing the numbers or distinctive marks of the sets. The cases and contents are weighed, and then taken to the field.

On arrival, a suitable traverse is chosen for the first experiment. In the writer's investigation, the traverse usually extended right across a field, and its length varied between 200 and 300 yards. The pencils are to be "planted out" at ten stations along the traverse², as follows. Starting at zero time, one pencil from each of the five cases is carefully inserted into the soil at the first station, and in a line at right angles to the line of traverse. The pencils are set at distances apart of approximately nine inches, and preferably in semicircular fashion round a growing plant. The top layer of soil mulch is removed before insertion, and the pencils pushed into the soil until their absorbing ends are at a distance of about five inches below ground level. The uncovered ends of the pencils are protected from the sun by a light covering of straw (cane trash), cloth or paper. Proceeding along the traverse to the next station, five more pencils are similarly "planted." The operation is repeated at each station until all the pencils have been placed. The total time taken to complete the traverse is noted. In the writer's investigation, this varied between 30 minutes for the moister soils, to 80 minutes for hard and dry soils. In the latter case, it was generally found necessary to prepare holes for the pencils by forcing a pointed iron rod (a stout nail) into the soil. The pencils are then pushed into these holes until contact is made between their absorbing surfaces and the soil. Unless great care is taken in this operation, the graphite points of the pencils are broken. If the broken pieces cannot subsequently be recovered, the whole experiment is spoiled; hence the advisability of previously blunting the pencil points by rubbing on sandpaper. The average time required to place a batch of pencils at each station is calculated from the total time taken to complete the traverse.

In similar manner, the second experiment is initiated along a traverse in a neighbouring field. Again the average time of each planting of a batch of five pencils is noted.

¹ Large pyralin tooth-brush cases, 7 inches long, by $1\frac{1}{4}$ inches diam. were used. The ventilating holes of these were closed by de Khotinsky cement. Cases and cement may be obtained from the Central Scientific Co., Chicago, U.S.A.

² The object was to obtain average results for the water-supplying power of the soil in sections of fields running parallel to contour lines. Each determination involved the use of ten soil-points; by using five sets of pencils, five replicates of each determination could be obtained; from these, probable errors were calculated. In estimating the water-supplying power of the soil of plots laid out for manurial or varietal trials, different arrangement and spacing of the soil-points would naturally be chosen.

After the lapse of three hours from the time of insertion of the first pencil in Exp. 1, the recovery of the soil-points is commenced. Each of the five pencils belonging to the first batch is, in turn, carefully withdrawn; its absorbing end wiped with a cloth to removed adhering soil, and the pencil quickly placed in its proper case opened to receive it. The services of an assistant are generally needed here. At the correct time, the second batch of pencils is likewise recovered, and so on throughout the series. Great care must be exercised in replacing the pencils in their cases not to leave the cases uncovered for a longer time than is necessary, otherwise evaporation from the moist ends of the pencils leads to serious errors.

On completion of the recovery of the pencils in the first experiment, the recovery of those of the second experiment is commenced after the lapse of three hours from the time of its initiation. This having been done, the cases and their contents are taken back to the laboratory, and re-weighed.

By these means, five replicates of single line traverses across each of two areas are obtained, yielding mean results which are each a measure of the moisture absorbed by ten similar soil-points during a three-hour contact.

EXAMPLES OF TYPICAL RESULTS.

The figures in the table (column 3) show the water-supplying powers after a prolonged period of drought of soils of different fields of a sugarcane estate. They are each the mean of five replicates, and are expressed as hundredths of a gram of water absorbed by one soil-point in a three-hour period. The probable errors of means were calculated by applying the formula

$$E_m = \pm 0.67 \sqrt{\frac{d^2}{n(n-1)}}.$$

If the difference between any two means is 3.8 times the probable error of either, the chance is 30 to 1 that this difference is significant and indicative of real variation in water-supplying power¹.

It will be noticed that the probable error of the mean tends to increase as the figure for the water-supplying power of the soil decreases. This implies that the reliability of the method becomes less as the water-supplying power of the soils examined approaches a minimum, and is due to the fact that increasing difficulty is experienced in obtaining

¹ Wood and Stratton, *Journ. Agr. Sci.* 3, p. 417, 1910.

uniform contact between the absorbing surface of the soil-point and the soil particles in dry soils.

For reference, the actual moisture contents of a certain number of the soils, calculated on an oven-dry basis, are included in the table (column 4). It will be seen that these figures bear no simple relation with those representing the water-supplying powers. Finally, in columns 5 and 6, the stage of growth and the condition of the cane plants growing in the soils are indicated. In deciding whether or no plants were showing signs of wilting, the opinion of an experienced planter was obtained. It may be added, however, that in every case the wilted plants subsequently recovered when wet weather set in.

Table. *Water-supplying powers of cane-field soils by the soil-point method.*

1	2	3	4	5	6
Field and soil number	Date of experiment	Water-supplying power of soil	Total moisture content	Stage of growth of cane plants	Condition of cane plants
Cls. 1	June 28, '21	4.69 ± 0.015	—	Plant canes	Vigorous
" 2	" 28, '21	4.08 ± 0.012	—	" "	"
Gms. 1	" 7, '21	3.69 ± 0.012	—	" "	"
C.G. 5	Apr. 25, '22	3.63 ± 0.013	37.9	1st ratoons	"
" 8	June 8, '21	3.45 ± 0.027	—	Plant canes	"
" 12	" 1, '21	3.26 ± 0.024	—	" "	"
" 2	Apr. 25, '22	3.18 ± 0.042	40.5	" "	"
" 1	June 2, '21	2.96 ± 0.048	—	2nd ratoons	Sprouting
" 11	Apr. 26, '22	2.82 ± 0.025	36.2	" "	"
" 2	May 28, '21	2.74 ± 0.031	—	Plant canes	Normal
" 10	" 30, '21	2.72 ± 0.040	—	1st ratoons	"
" 5	" 28, '21	2.71 ± 0.026	—	" "	Vigorous
" 10	Apr. 26, '22	2.53 ± 0.038	40.1	" "	Normal
" 3	June 2, '21	2.39 ± 0.025	—	Plant canes	"
" 11	May 30, '21	2.32 ± 0.048	—	1st ratoons	Sprouting
" 7	" 31, '21	2.28 ± 0.072	—	" "	Normal
Skt. 2	June 6, '21	1.71 ± 0.066	—	Plant canes	Wilting
C.G. 21	" 1, '21	1.59 ± 0.067	—	Fallow*	—
Skt. 1	" 6, '21	0.52 ± 0.067	—	Plant canes*	Wilting

* Ground hard and cracked.

It is of interest to compare Mason's laboratory figures for the water-supplying power of soils at the wilting point with the writer's results obtained in the field. In each case standard pencils were employed, and the same machine used for sharpening them. Mason's mean result is 1.41 ± 0.031 hundredths of a gram of water absorbed by one soil-point in three hours¹. The limits of variation were 1.61 and 1.20 in a series

¹ *West Ind. Bull.* 19, p. 151, 1922.

of soils of widely varying texture and colloid content¹. The writer's figure is 1.71 ± 0.066 for a plot of well-established cane plants. This figure proved to be somewhat too high, however, since the plants subsequently recovered. The approximate similarity between laboratory and field results yielded by the soil-point method in this critical trial indicates that considerable confidence may be placed in the method as a practicable means of attacking many important ecological problems that have so far baffled investigation.

SUMMARY.

1. Attention is drawn to Mason's modification of Livingston's soil-point method of directly estimating the water-supplying power of a soil *in situ*. Mason used ordinary lead writing pencils as soil-points.

2. This method, heretofore tested only in the laboratory, has been employed by the writer in an ecological field study. Details of the procedure adopted are described, and the reliability of the method is indicated by the presentation of a series of mean results with their corresponding probable errors.

3. It is concluded that the method is practicable; it should prove of considerable usefulness to workers in ecology.

¹ Mason used maize plants as indicators. Briggs and Shantz (*Bur. Plnt. Ind., U.S. Dept. Agric., Bull.* 230, 1912) have demonstrated that the variations exhibited by different species of plants, at least, of the commoner crop plants, in their ability to reduce the soil moisture to the point at which permanent wilting sets in are practically negligible, and, when significant, may be traced to imperfect root distribution rather than to specific differences in the magnitude of the force of inhibition at their absorbing surfaces.

WEST INDIAN AGRICULTURAL COLLEGE,

TRINIDAD, B.W.I.,

May 10, 1923.

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THE DETERMINATION OF THE BEST METHOD FOR ESTIMATING POTATO YIELDS, TOGETHER WITH A FURTHER NOTE ON THE INFLUENCE OF SIZE OF SEED ON THE CHARACTER AND YIELD OF THE POTATO. III.

BY REDCLIFFE N. SALAMAN, M.A., M.D.

(With Eight Text-figures.)

THE work undertaken in 1922 was in the main a continuation of that done in 1920 and 1921, the results of which have already been published, and the object of which had been to determine the relation between the size of the seed tuber-sets and their resultant crop, and the further relation between the amount of heavy ware in the crop and the size of the seed.

This year the same line of research has been followed. In addition, however, an effort has been made to discover what is the best shape, what the best size of plot, and what the most desirable number of repetitions of the same, to ensure the highest practicable accuracy, as determined by the lowest probable error of the difference of the mean, in the estimation and comparison of yields of different varieties of potato.

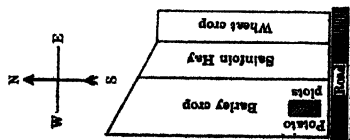
The variety used was, as in the previous experiments, Barley Bounty, the seed of which had been grown in Scotland in 1921; it was sprouted in boxes in Barley and planted on May 8th. This variety is very highly resistant to Leaf Roll, if not indeed immune to it. It is less resistant to Mosaic, whilst to the attack of *Phytophthora* it exhibits a resistance considerably above the average. These qualities, with its spreading habit and heavy cropping capacity, render it especially serviceable for field tests. The ground, which was level and chosen as being of an equable texture and fertility had been dunged in the previous autumn with ten tons of farm-yard manure per acre. Four cwts. superphosphate, one-and-a-half of ammonia sulphate and potassium sulphate were added at the time of planting, being put up the drills in weighed quantities.

The scheme of planting is shown in Fig. 1. It consists of 30 drills, exclusive of guard rows of the same variety on all sides of the entire

Description of seed sets

- A 40 oz. each
- B 20 " "
- C 10 " "
- D 16 " "
- E 138 " "
- F 10 " "
- G 8 " "
- H 35 " "
- I 35 " "
- J Outgrowth, cut. 1 oz. each
- K " " 5 oz. "
- L " " 25 oz. "
- M " " 175 oz. "
- N " " 175 oz. "

Plan of part of farm



Weight of long rows—8 plots on end															No. of row
384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	
5	5	4	10	6	6	0	12	2	3	12	12	4	4	6	Av. misses 5-7 Belt 5 Av. wt. 74 lb.
77	74	61	62	58	80	10	71	81	47	75	68	78	85	70	
D	E	I	D	F	G	4	K	B	C	H	E	F	G	D	
3	4	8	3	5	12	3	L	5	7	11	6	7	9	14	Av. misses 5-13 Belt 4 Av. wt. 75 lb.
79	74	37	70	80	10	2	J	77	61	70	80	72	44	74	
G	D	G	E	I	F	H	F	I	D	1	M	C	E	B	
6	0	7	6	9	6	7	5	12	10	13	7	4	6	7	Av. misses 5-4 Belt 3 Av. wt. 70 lb.
70	91	69	71	43	62	71	50	63	13	K	13	89	70	75	
I	F	I	D	G	E	D	G	C	H	B	1	3	8	5	
7	5	11	3	7	5	9	3	6	8	9	8	8	5	4	Av. misses 5-2 Belt 2 Av. wt. 81 lb.
66	80	42	77	58	66	46	74	75	63	78	66	73	53	78	
E	I	G	F	E	D	I	H	G	F	E	D	C	B	1	
4	9	7	2	2	4	7	5	2	7	2	3	3	4	0	Av. misses 5-4 Belt 1 Av. wt. 84 lb.
80	70	79	68	65	76	69	72	85	80	93	85	92	0	81	
30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	
30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	

Fig. 1. Framing the entire plot is a double row of Barley Bounty. The numbers on each plot are the number of missing plants and the weight of the crop respectively.

plot, each drill contained 250 tubers planted so that the distance between the centre of the sets was 12 inches and the distance between drills was 32 inches. Each drill was subdivided by pegs into five equal groups of 50 sets, and in consequence the whole plot became broken up into five transverse belts.

Rows 1-15 were planted with unselected seed of Barley Bounty, from which only the very heaviest and the very smallest tubers had been removed, the former for examination as group *A* (see later), the remainder, including chats about half an ounce in weight, was, after thorough mixing planted with the rest of the group of sets *A-I*, under the strictest supervision in one day, viz. May 8th, 1922.

The remaining 15 drills were planted at the same time with the same amount of artificial manures on the same day with 5 or 11 lots of 50 tubers each (excepting *A*, *J*, *K* and *M* in which the number of sets in each plot was less).

The first 15 drills containing 75 replications of 50 sets each of the mixed seed of one variety, was especially designed for arriving at some conclusions as to the best means of estimating yield. The measure of accuracy employed was the size of the probable error of the mean, calculated by the method known as the "least squares," for different groups of plots arranged either end on or side to side. A chequer board of square plots with an equal number of sets in each was not used for the reason that in the author's opinion this method of testing is all too costly in labour, indeed without much skilled assistance, practically impossible, and the results are not only not better, but actually not so good as when the long drill method is employed. It has been possible, thanks to the Director of the National Institute of Agricultural Botany, to compare the results obtained from three chequer board trials carried out with the very greatest care, with the results of the experiment here described.

It was felt that one of the first requirements in respect to Yield Tests of Potatoes is to arrive at a trustworthy and simple method—which in practice means some form of chequer board composed of long drills as opposed to squares. Further, by keeping the drills wide apart, the need for planting some neutral variety between varieties being tested disappears.

The scheme which was here adopted allows of plots measuring $\frac{3}{32} \times 70$, $1 \frac{1}{8} \times 8$, $10 \frac{1}{8} \times 6$, $3 \frac{1}{2} \times 7$, $1 \frac{1}{8} \times 8$, $\frac{1}{8} \times 8$, $\frac{1}{4} \times 7$, $\frac{1}{4} \times 1$, $\frac{1}{2} \times 1$ of an acre being employed and each replicated at least five times.

The potatoes grew well and equably, there was some slight Mosaic,

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but no Leaf Roll or Blight. The crops were raised on October 9th, weighed, and a 10 lb. sample taken of each of the 170 plots present.

It will be well at first to confine our attention to the drills 1-15 on which the 75 plots in 5 belts of unselected seed were planted.

Missing plants. In every crop of potatoes a certain percentage of the sets fail to produce a plant for some reason or another, and it is therefore of importance to determine whether "misses" occur in all plots with equal frequency, or whether there be a relation between their occurrence and other factors. Two such factors present themselves here, the one, the position of the plot on the field, and the other, the character of the seed. We shall therefore consider here the number of "misses" per 50 "sets" occurring in all the groups of seed sizes employed on the second half of the ground, viz. between drills 16 and 30, where each seed size is represented in every part of the trial ground, as well as the "misses" found in the 75 plots where the seed is similar and unselected.

The number of missing tubers is shown in Fig. 1 as the upper numeral on each plot.

Considering drills 1-15 (unselected seed) we find that the "misses" in the long drills (250 sets) vary from 7 to 29, with an average of 21·8 per long row, or 4·37 per plot of 50 sets (see Table I). If now the "misses" in the seven rows of the eastern half of the total plot be compared with the seven on the western side, we find that the latter has very considerably more "misses," viz. 173 as compared with 126, or 4·94 per plot of 50 sets as compared to 3·62. If now the "misses" in each belt, as well as those in each west and east half, be considered, the averages per 50 sets are, as shown in Table I.

Table I.

	Average of "misses" in western half rows 9-16	Average of "misses" in eastern half rows 1-7	Average of "misses" in whole belt
Belt 1	2·28	2·38	2·4
„ 2	4·0	2·14	3·2
„ 3	7·14	3·43	5·4
„ 4	5·55	4·43	5·13
„ 5	5·71	5·71	5·7
Average	4·94	3·62	4·37

From these figures it is clear that there is a progressive increase of "misses" from east to west, and an almost equal increase from south to north. In general, the "misses" increase throughout the whole plot on a more or less direct route from the south-west corner to the north-east.

This steady trend amongst the "misses" is not due to the character of the land, which as we shall see though as nearly uniform as could be found

in this district, improved in fertility from north to south, nor is it due to the nature of the seed, which in these 15 long drills is all of the same character. The explanation, however, is not far to seek. Along the southern border of the plot at a distance of 10 yards from the plot, runs a road along which a certain amount of agricultural traffic passes daily, sufficient to disturb the crows, who are the chief offenders amongst the birds who exploit the fresh set potato tubers. The eastern border of the plot is that nearest to the remainder of the farm, and for the same reason the birds tend to avoid that portion and concentrate their attention on the north-western portion of the plot.

"Misses" in a potato crop, however, can by no means be ascribed solely to the depredations of birds. Hence it is of value to note the proportion of "misses" in each of the various groups of plots in relation to the size of their sets.

The sizes of the seed plots and the number of sets and replications of each as planted in rows 16-30 inclusive are shown in Table II.

Table II.

Class	Weight of seed tuber, oz.	Size of plot	Number of sets per plot	Number of replicates	Average of "misses" per plot of 50
<i>A</i>	4.0	$1\frac{1}{8} \times 4.5$	10	5	9.0
<i>B</i>	2.66	$3\frac{1}{2} \times 7$	50	5	5.4
<i>C</i>	2.0	$3\frac{1}{2} \times 7$	50	5	6.4
<i>D</i>	1.6	$3\frac{1}{2} \times 7$	50	11	4.82
<i>E</i>	1.33	$3\frac{1}{2} \times 7$	50	11	4.63
<i>F</i>	1.0	$3\frac{1}{2} \times 7$	50	11	5.9
<i>G</i>	0.8	$3\frac{1}{2} \times 7$	50	11	5.8
<i>H</i>	0.57	$3\frac{1}{2} \times 7$	50	5	9.0
<i>I</i>	0.35	$3\frac{1}{2} \times 7$	50	11	9.1

Class *A* may be left out of account in this consideration, being but one-fifth the size of the others and the total number of its sets being but 50 compared to 250 of *B*, *C* and *H*, and 550 of *D*, *E*, *F*, *G* and *I*.

The "misses" in seed groups *B*, *C*, *D*, *E*, *F*, *G* are all more or less equal in amount but with groups *H* and *I* a decided difference sets in, the average of missing plants jumping from between 5 and 6 per plot to 9. This change is not due to any disadvantage of position for, as will be seen in Fig. 1, *H* is represented in all the belts and *I*, which occurs twice in belts 1, 3, 4 and 5, is found three times in belt 2, the more fertile end of the plot. We may therefore safely conclude that the increase of "misses" in *H* and *I* is due to an intrinsic property of the seed. In other words, seed tubers below .8 oz. in weight are at a disadvantage compared with all other seed sizes.

We must look therefore to some cause other than soil conditions and the actual mass of the seed-set to account for the high ratio of "misses"

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in these two classes. It will be understood that the various seed classes *A-I* have been selected from the mass crop of the preceding year. Now experience has shown, and it is confirmed by numerous writers, that plants infected with mosaic disease tend to produce smaller tubers than those non-infected. The produce of such infected plants as occurred in 1921 was mixed with that of all the others and hence when a selection is practised specially designed to recover small seed, it is obvious that in such a selection the produce of mosaic infected parents will be over-represented in comparison with that in the selection of the larger sized seed-tuber groups. There is in classes *H* and *I*, therefore, an indirect selection of mosaic infected tubers and these, as has been repeatedly found, are less inclined to propagate new plants than non-infected seed, whatever its weight may be. Hence the large rise in the proportion of misses in whole tuber-seed sets of a weight under .8 oz.

The probable error of the number of missing plants in the class groups *D*, *E*, *F*, *G* and *I*, in which the plots are repeated elevenfold is .7. The differences in the averages of the number of missing plants in class *D* and *I*, viz. 4.18; *E* and *I*, viz. 4.37; *F* and *I*, viz. 3.2; and *G* and *I*, viz. 3.3; are all above four times the p.e. and hence undoubtedly of significance. Indeed the difference between the averages of the number of "misses" of classes *E* and *F*, viz. 1.27, is nearly double the p.e. and may well be due in part to the action of selection.

It may be stated therefore that when seed tubers of less than 1.33 ozs. in weight are selected from a crop for seed purposes there is a very considerable danger of planting tubers tainted with mosaic (or other virus disease), whilst if chats of less than .8 of an oz. are employed, a positive selection in favour of infected tubers has certainly taken place if, as is most probable, some virus disease was present in the preceding year's growing crop.

F. Stewart⁽⁵⁾ showed that a very considerable part of the loss due to a missing plant is made good by the extra crop produced by the contiguous neighbours of the missing plant. When one plant was absent the two neighbouring ones made good 50 per cent. of the loss; but when two or more are absent the loss was not made up to the same extent. In the experiments under discussion no note was taken as to whether the losses were consecutive or not, and therefore it was not possible to use Stewart's figures to calculate the approximate maximum crop assuming no plants to be absent.

Rows 1-15 comprising 75 repetitions of the same seed-tuber material offered opportunities for investigating the problem on other lines. In

Table III.

Belt	Actual average weight of plot	Average weight of plots free of "misses"	Estimated yield allowing 50 % made good	Estimated yield allowing full replacement
Belt 1	84.5	89.7	86.5	89.0
" 2	81.7	86.3	84.0	87.0
" 3	76.0	84.5	80.5	85.5
" 4	75.0	83.0	80.0	84.5
" 5	74.0	78.0	78.5	83.75

the present trials we have two methods of estimating the value of the missing plants. We can seek out those plots in each belt which are free from "misses" and we can compute the potential crop of each belt assuming that the crop would have increased in proportion to the number of "misses," and alternatively we can calculate the probable crop on the assumption that on the whole the "misses" are independent and not consecutive and that the neighbouring plants make good half the deficiency. In Table III these figures are given.



Fig. 2. The continuous line shows the number of missing plants in each crop weight class, in Rows 1-15. The broken line shows the number of plots of each such class, in Rows 1-15.

In belts 1 and 2, where we have four and three plots respectively free of missing plants, the average crop is very close to the estimated

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pro rata crop. In belt 3, where there are two plots only without "misses," the average is again very fairly close to the *pro rata* estimate, and in belts 4 and 5, where there is only one plot in each free from "misses," the actual yield of such plots are considerably below the estimated crop.

In all cases, however, except that of belt 5, the actual yield of the plots without "misses" is much nearer the estimated yield when allowance for making good the whole loss by neighbours is made than when only 50 per cent. is allowed for.

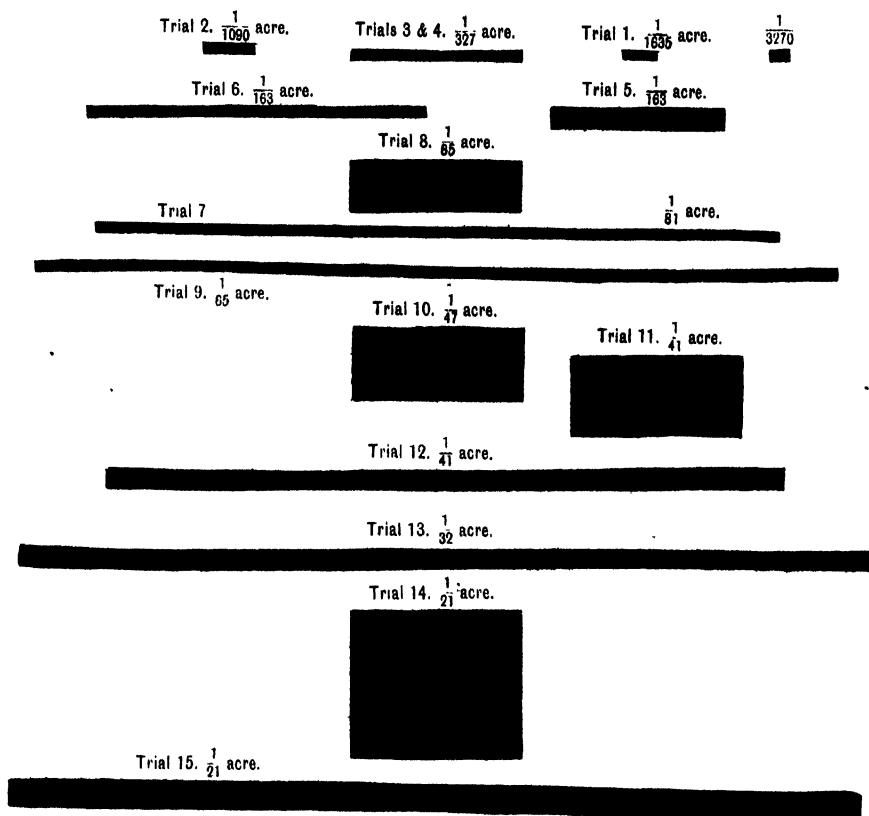


Fig. 3.

The very close agreement of the average yields of full plots in belts 1, 2 and 3 to the estimated yield is sufficient to allow these latter to be taken as approximately correct measurements of the potential yields of the belts in respect to the variety employed and the general conditions under which the experiment took place.

The relation of the number of "misses" in each experimental plot to the weight of the crop of the plot is shown in Fig. 2. The relation is, as would be expected, such that the smaller the crop the larger the number of "misses," but as one approaches the highest crop weight classes the curve becomes rather irregular. This irregularity is doubtless due in the main to the small number of plots falling into these high classes, but may also be influenced by the fact that the fewer the "misses" the more likely are they to be isolated rather than consecutive, and therefore the more

Probable error expressed in percentage of weight of yield.

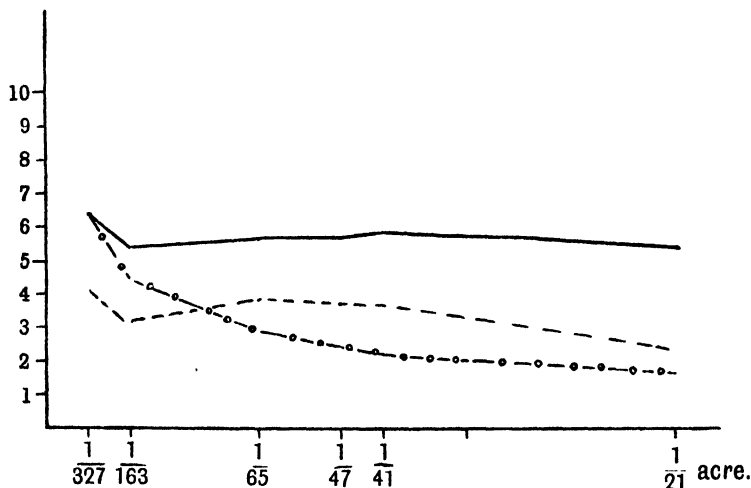


Fig. 4. Curves representing the changes in value of the probable error when the trial plots are short and thick.

The continuous line — represents the p.e. of the actual weights.

The discontinuous line - - - represents the p.e. of the "corrected" weights.

The interrupted line -o-o- represents the theoretical change in value of the p.e. in relation to the successive changes of area.

readily is the loss made good by the neighbouring plants. That this method of correction though accurate enough may prejudice calculations based on the corrected yields will appear when the p.e. of the yields for various areas is estimated both for the corrected yield and the actual one. When the areas are elongated (see Fig. 3) and but one drill wide the p.e. of the corrected yields falls somewhat below the actual one for the area in question, *i.e.* there is less variability between such corrected yields than amongst the actual yields of the areas in question. But when the plot, still elongated, is 2 or 3 drills wide, the p.e. of the

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corrected yields tends to become greater than that of the actual for the same sized plot (see Fig. 5).

Probable error expressed in percentage of weight of yield.

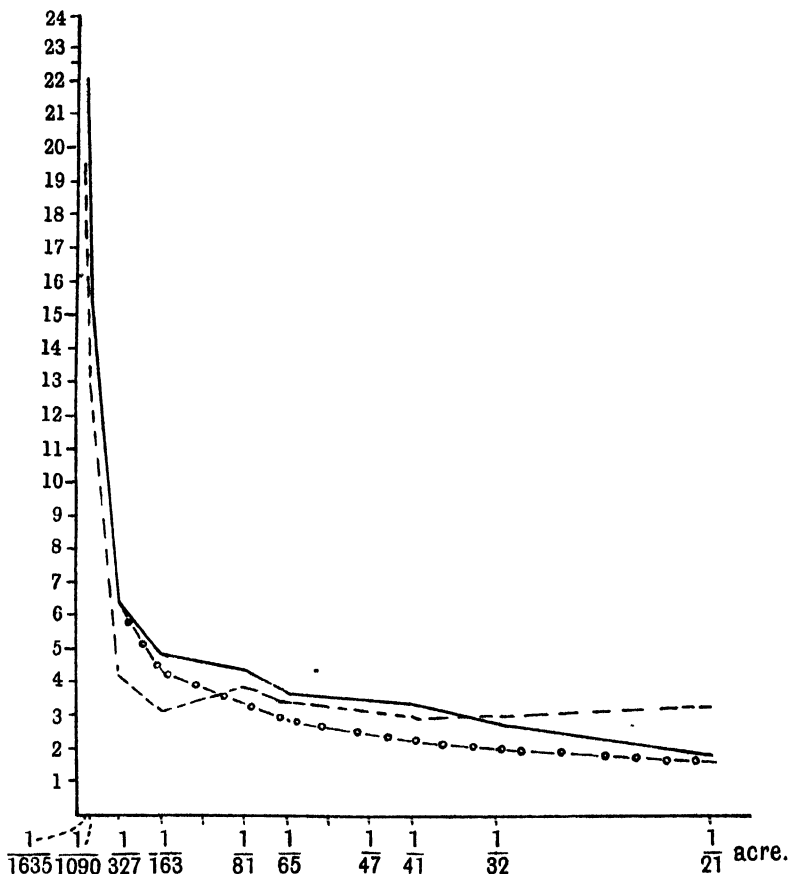


Fig. 5. Curves representing the changes in the value of the probable error when the trial plots are long and slender.

The continuous line — represents the p.e. of the actual weights.

The discontinuous line - - - represents the p.e. of the "corrected" weights.

The interrupted line -o-o- represents the theoretical change in value of the p.e. in relation to the successive changes of area.

In contrast to the relation just recorded in regard to the elongated areas, the p.e. of the corrected yields of the short broad plots is very much less than that calculated for the actual yields of the respective areas (see Fig. 4).

Indeed there are two peculiar features in respect to the curves, Figs. 4 and 5. The one is that whilst increase of area in the long plots reduces the p.e., in the short thick areas, the p.e. remains stationary or almost so. The other, that corrections for missing sets in the long areas after a certain area is reached renders the variability of the corrected yields actually greater than that for the uncorrected for similar areas.

The explanation is to be found in the different causes and directions of the variable factors at work. These are:

(a) A general irregular "chaotic" variation due to a variety of non-calculable causes—weather, temperature, wind, accidental circumstances affecting one or another plant. Such variation has no direction and its effect on the p.e. will vary with the square root of the area involved. Its effect will be felt in all plots whatever their shape.

(b) A northern to southern variation in fertility of the soil. This is very definite, and steady in its increasing value southwards.

(c) An east to west variation in soil fertility which steadily grows in the westward direction. The rate and force of "b" and "c" are unequal, so that although the N.-S. axis of the experimental plot is 250 ft. and the E.-W. axis is but 45 ft., the difference between two plots at the extreme N. and S. will vary but little from that of a pair at the extreme E. and W.

(d) There is a variation caused by birds destroying the tuber sets. This variation may be resolved into two; one in which the onslaught of the birds is more or less general and indiscriminate over the whole experimental plot; the other, superimposed on the former, where the birds have, for reasons already given, pursued their ravages generally from S.E. to N.W. The first effects will be included in the class (a) or chaotic group of variations, and the other will, to some extent, affect the tenor of the results.

In the long plots the N.-S. variation, which is the most important, is eliminated, the E.-W. variation is still a work, whilst exerting its influence in the opposite direction and neutralizing its effect is the directive part of the variation (d) due to birds. Hence the p.e. for the long plots should closely approximate to the theoretical, as it indeed does, becoming progressively less as the areas increase.

When, however, the long areas are corrected for "misses," the E.-W. variation is now no longer neutralized by the variation due to the birds, hence the p.e. will not fall indefinitely with the size of the plot, because it is dependent on a source of variation, which is constant in both direction and force, viz. fertility increase from E.-W. and not, as before,

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merely on the "chaotic" variation. In consequence, a point is reached when the "corrected curve" crosses the actual, and remains at a higher and constant level.

The short and thick areas are subject to the full force of the N.-S. variation and equally to that of the E.-W. variation, as were the long areas. The curve for the p.e. will not fall with the increase of plot area because the main source of variability is constantly at work and equally so, no matter how thickened such a short area may be.

Correction for "misses" tends to neutralize the N.-S. variation, but on the other hand intensifies the E.-W. variation. The balance of these effects will keep the variability of the corrected yields permanently below that of the actual, which will be shown by the lower range of values for the p.e., of the corrected areas. The constancy of the variation now due almost entirely to the E.-W. effect is shown by the almost straight course taken by the curve. It will be seen, therefore, that correction made "*pro rata*" to the number of missing plants may produce results indicating a considerably greater or lesser variability than is really present and hence may be quite inaccurate.

THE INFLUENCE OF SIZE AND SHAPE OF PLOT ON THE ACCURACY OF YIELD DETERMINATION.

Figs. 1 and 3 show the shape, size, disposition and number of replications of the plots which were tested. The areas of the plots used were $\frac{1}{3270}$, $\frac{1}{1635}$, $\frac{1}{1090}$, $\frac{1}{547}$, $\frac{1}{273}$, $\frac{1}{182}$, $\frac{1}{137}$, $\frac{1}{109}$, $\frac{1}{82}$, $\frac{1}{64}$, $\frac{1}{54}$, $\frac{1}{45}$, $\frac{1}{36}$, and $\frac{1}{27}$ respectively of an acre. The plots were replicated from 5 to 75 times. In all cases the p.e. of the difference of the mean was obtained, and in Table IV these are given both in pounds weight and in percentage of the average yield. The p.e. for one pair of plots, as well as for the full number of pairs of plots examined, is also stated. As a measure of comparison, the p.e. for one pair will be taken.

In all cases except two the p.e. was determined by calculation of the differences of all pairs of plots and not of adjacent ones only.

In the case of the calculation in trials Nos. 3, 5 and 6, Table IV, it was undesirable to calculate the p.e. by the same method, as the number of pairs involved would have been 2775 and 435 respectively. The p.e. in this case was calculated from the differences between adjacent pairs of plots.

The p.e. of all adjacent $\frac{1}{327}$ acre plots both in the horizontal and vertical directions was calculated for the entire 75 plots (see Table IV) and was found to be 6.3 per cent. for a single pair.

Table IV. Probable error of the mean expressed as percentage of average of yields.

Trial	No. of sets per plot	Area of single plot, acre	No. of plots "N"	% of missing plants each plot	P. e. of mean of single pair of plots	P. e. of mean of single pair corrected for "misses"	P. e. of mean of single pair corrected for "misses"
1	10	1 ¹ / ₁₀	10	16.0	22.0	7.1	6.2
2	15	1 ¹ / ₁₀	5	28.0	15.5	6.95	5.8
3	50	3 ¹ / ₁₀	75	8.7	6.3	0.73	0.48
4	50	3 ¹ / ₁₀	75	8.7	6.5	—	—
Calculated as a mean of p. e. of single plot in each of the 5 belts							
5	100	1 ¹ / ₁₀	28	8.0	5.35	1.01	0.59
6	100	1 ¹ / ₁₀	28	8.0	4.77	1.13	0.60
7	200	3 ¹ / ₁₀	15	8.2	4.45	1.15	0.97
8	250	3 ¹ / ₁₀	15	8.7	5.6	1.45	0.96
9	250	3 ¹ / ₁₀	15	8.7	3.62	0.93	0.89
10	350	4 ¹ / ₁₀	10	8.5	5.6	1.77	1.14
11	400	4 ¹ / ₁₀	8	8.2	5.8	2.04	1.25
12	400	4 ¹ / ₁₀	7	8.2	3.33	1.62	1.03
13	500	4 ¹ / ₁₀	7	8.6	2.75	1.04	1.14
14	750	4 ¹ / ₁₀	5	8.7	5.4	2.42	1.05
15	750	4 ¹ / ₁₀	5	8.7	1.8	0.81	1.5
Plots made of 2 single plots laterally							
						2	on end
						4	"
						5	laterally
						5	on end
						7	"
						8	laterally
						8	"
						4	on end and 2 thick
						4	"
						5	"
						15	laterally
						5	on end and 3 thick
						5	"

Theoretical Curve.

$\frac{1}{3\frac{1}{2}}$ acre p.e. = 6.3 %	$\frac{1}{3\frac{1}{2}}$ acre p.e. = $\frac{6.3}{\sqrt{5}}$ = 2.8 %	$\frac{1}{3\frac{1}{2}}$ acre p.e. = $\frac{6.3}{\sqrt{10}}$ = 2.0 %
$\frac{1}{3\frac{1}{2}}$ " = $\frac{6.3}{\sqrt{2}}$ = 4.5 %	$\frac{1}{3\frac{1}{2}}$ " = $\frac{6.3}{\sqrt{7}}$ = 2.4 %	$\frac{1}{3\frac{1}{2}}$ " = $\frac{6.3}{\sqrt{15}}$ = 1.62 %
$\frac{1}{3\frac{1}{2}}$ " = $\frac{6.3}{\sqrt{4}}$ = 3.15 %	$\frac{1}{3\frac{1}{2}}$ " = $\frac{6.3}{\sqrt{8}}$ = 2.22 %	

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The p.e. of a single $\frac{1}{327}$ acre plot from a pair of plots taken at random as found in all the five belts separately averages 6.5 per cent., which agrees closely with the value 6.3 obtained by considering adjacent plots over the whole area. It may be taken therefore that 6.3 is the p.e. for one pair of plots $\frac{1}{327}$ of an acre in size.

The areas of $\frac{1}{3270}$, $\frac{1}{1635}$ and $\frac{1}{1000}$ of an acre are found scattered in the rows 16–24. Such plots contain 5, 10 or 15 sets respectively and are each repeated five times. The p.e., Table IV, trials 1 and 2, and Table VI are 22 and 15 per cent. respectively, indicating the utter unreliability of such small plots insufficiently replicated. It is not proposed to deal further with them except to note how even the increase of so small a plot as $\frac{1}{1635}$ by one-half its size materially improves its accuracy.

The arrangement of the experiment was such that the crops of plots of very various size and shape could be examined. Essentially the difference to be attained in respect to shape is that one group may be short and relatively broad, and the other long and relatively narrow. The yields of crops of the short group will be considered first (see Table IV and Fig. 4).

The single 50 tuber plot of $\frac{1}{327}$ acre is in trial 5 doubled and 28 such 100 tuber plots taken in adjacent pairs all over the area produce crops which (rows 1–15) have a p.e. of the mean for one pair of 5.35 per cent. Areas made up of five, seven, eight and fifteen such single 50 tuber plots and representing areas of $\frac{1}{65}$, $\frac{1}{47}$, $\frac{1}{41}$, $\frac{1}{21}$ of an acre respectively produce yields having p.e. of 4.77, 5.6, 5.8 and 5.4 per cent. respectively. In short increase of the area of the plot when such increase is occasioned by broadening only of the plot in no way improves the accuracy of the trial. In Fig. 4 the above results are shown graphically and comparison is there made with the theoretical curve of the p.e. of the yields of the different areas, which varies as the square root of the area, and a still further comparison is made with a curve showing the range of the variability as expressed by the value of the p.e. when correction has been made in each plot for the missing plants. It will be seen that this latter curve is considerably lower than that for the actual yields and shows some approximation, though not a close one, to the theoretical.

Examination of the variability in differing areas when the difference is induced by increasing the area by adding the short rows end to end exhibits an entirely different result.

Reference to Table IV and Fig. 5 shows that the increase of the area by adding two short rows together end to end reduces the p.e. at once

to 4.77 per cent., whilst by further enlarging the area and increasing the length of the plot the p.e. of the mean of the yields is uninterruptedly reduced till plots of $\frac{1}{21}$ of an acre so constituted exhibit a variability expressed by the p.e. of 1.8 per cent. as compared to 5.4 per cent. for an area of equal size made up of 15 short rows taken side by side.

In Fig. 5 the fall of the values for the p.e. is shown graphically and it will be seen not only that its fall is perfectly regular but that it follows both in degree and character the theoretical curve with great closeness.

It has been already pointed out that the curve for the corrected values of the yields of the different areas, at first slightly lower than that for the actual yields, tends to increase above the latter and the explanation has been given above. It may be noted, however, that even so the curve for the corrected values of the elongated areas follows the actual one far more closely than does that for the broad short area its counterpart.

The result demonstrating the vast superiority of the long plot over the short broad one is, of course, only necessarily true for this particular experiment. The fact that the field upon which the potatoes were grown shows a definite soil variation along the length of the plots, as well as the fortuitous circumstances which caused the ravages of the crows, to fall in such a direction that all long rows were more or less equally affected in some part of their course, doubtless sufficiently explain the striking advantage attained by the long versus the broad areas in this particular field experiment.

Still it may be claimed that the long plot is in many ways to be preferred over the broad one. In no piece of land—certainly in this part of the country—can one be certain of uniformity of texture or fertility. Previous farming experience with this particular soil will have shown in which direction the fertility varies. With such knowledge already gained it is only necessary to lay out the yield trial so that the drills lie along the same axis as that in which the soil change has been observed, to reduce the range of variability due to soil to a minimum, for each drill will then partake of both the good and the less good soil in the area used. If, however, no note be taken of the direction in which the fertility of the soil varies, and the plots be more or less square and scattered, the chances of each variety sharing equally in the varied soil conditions is materially reduced.

It is true that by only comparing adjacent plots some of the error thus introduced will be neutralized, but by the long plot method laid out as advised, the plots may be compared at random.

A further point in favour of the long plot is the ease in working the

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same. By this method the sets may be freely ploughed in and all the subsequent procedures performed by horse-labour instead of by hand. It has only been found necessary to have a man follow the plough to immediately replace the stakes between plots or sections of the row. Indeed in the trials here recorded the drills were all rolled in by a horse-drawn 8 ft. roller. In this case a handful of chaff is placed around the insertion of each stake or label and the latter momentarily removed to allow the roll to pass. No confusion or trouble has arisen from this procedure, which has been used by the writer for the last three seasons.

It is hardly necessary to emphasize the reduction in cost in respect to the long drill plot in comparison to the short square one. In the latter all work must be done by hand and every stroke of it supervised. In the former, supervision is also necessary but it is far less strenuous and exacting.

Assuming, as indeed the results depicted in Figs. 4 and 5 would appear to amply justify, that the most desirable area is a long, narrow one, it is necessary to consider certain further points in relation to it:

- (a) At what distance apart should the tubers be planted?
- (b) At what distance apart should the drills be drawn?

The distance between sets in the experiment here described was 1 ft.—accurately measured by means of a foot-long rod between the centres of each consecutive tuber set. Whilst it is not assumed that 15 or 18 ins. might not give equally good results, the distance of 1 ft. is recommended for two reasons. In the first place, when sets are reasonably close together and one fails the chances of the neighbouring ones making good the loss are greater where the distance between them is not too great—for it is obvious that if the sets were so far apart—say 2 ft. or 2 ft. 6 ins.—each plant would have at its command the full complement of soil of which it could make use and the loss of an intervening plant would remain without effect on its neighbour.

Another reason for using a distance of 1 ft. is that it renders calculations rather more easy.

As regards the distance between drills, it is considered that 2 ft. 6 ins. should be the lowest. The reason for this is, that whilst in an experiment such as the one under consideration, where one variety only is being used, the effect which the one drill plot may have on the one next to it is of no matter, when the two contiguous plots contain two varieties of markedly different habit of growth—one possibly strong growing and spreading, the other small of top and low lying—it is possible that the former might so overshadow the latter as to seriously

hamper its growth. In the writer's opinion a distance between drills of 2 ft. 6 ins. is possibly the lowest one for safety if the varieties are more or less alike in habit of growth. If, however, the varieties were as diverse in character as suggested above, then probably a drill width of 3 ft. would sufficiently safeguard the accuracy of the trial. Although no direct experiments dealing with this matter of drill width in respect to yield trials has been made, the writer has found that when growing seedlings, in their first year it is not safe to have the drills less than 4 ft. apart if lateral interference is to be avoided. It is of course possible to introduce an intermediate guard row of some variety between every pair of drills, but it is felt that this procedure, whilst complicating the experiment, may, in reality do very little to combat this particular source of error, and that it is far better to keep the drills wide apart, probably employing a 3 ft. distance as a standard.

The size of the plot. If the plots are to be of the nature of single or double drills, it is necessary to consider what sized area is the most advisable.

If in the testing for yield of several varieties, the principles enumerated by T. B. Wood and Stratton⁽⁶⁾ be laid down, viz. that no difference in the mean of two or more varieties is to be deemed significant which is not above a 30 : 1 chance against it being due to a mere variation of soil, then a difference equal to 3.8 times the value of the p.e. of the difference of the mean is necessary as the minimum significant difference between means to be insisted on. If we further require as a practical measure that a significant difference of yield between any two varieties *A* and *B* must be under 10 per cent. of the value of *A*, we have a useful guide, for then $p.e. \times 3.8$ must not exceed 10 per cent.

Again, in testing for the yield of potato varieties it generally occurs that one or more of the varieties are new ones and cannot be obtained in large quantities. Hence the least number of tubers required to allow of a reasonably accurate result is a point which must be determined.

One hundredweight of seed tubers which have passed over a 1¼-inch riddle and through a 2-inch one, the normal trade usage for seed tubers contains at least 800 tubers. The following are the actual numbers contained in a hundredweight of the following varieties as supplied by a wholesale seed merchant.

1 cwt. of	Barley Bounty	contains	870	seed tubers.
1	„	British Queen	„	905
1	„	Dargill Early	„	990
1	„	King George	„	800
1	„	Nithsdale	„	907

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If 1 cwt. of seed tubers are available and the whole quantity is to be used for a test on a single station, it would be possible to plant eight plots of 100 tubers which (see Table IV) may be expected to have a p.e. of 4.77 per cent. for a single pair or 1.7 per cent. for eight pairs. Or if four plots of 200 tubers each were employed, the probable error would be for four pairs of such plots 2.2 per cent. In either case $\text{p.e.} \times 3.8$ would be well below 10 per cent., the margin desired within which a significant difference may be assumed.

If the number of tubers available were sufficient, the best sized plot as judged from the results here recorded would be long drills of 250 tubers. These gave a p.e. for one pair of 3.62 per cent., and fifteen such plots would have a p.e. of .93, which would make a difference of 3.5 per cent. a significant one. When the differences between the p.e. for a single pair of plots of 50 tubers, 100 tubers, 200 tubers, 250 tubers on end be reviewed, it will be seen that the increase of number of tubers from 50 to 100 reduces the p.e. from 6.5 to 4.77 but a greater increase from 100 tubers to 200 only reduces the p.e. from 4.77 to 4.45, hence for practical purposes a plot containing 100 tubers on end is amply large enough¹.

The number of replications desired obviously depends on the size of the plot and on the quantity of material available—from five to eight repetitions would appear to be both practical and sufficient to give the trials the required degree of accuracy.

It is of interest indeed to note how little the p.e. for a single pair varies by increasing the number of plots—thus the calculation for the p.e. of a single $\frac{1}{32}$ acre plot yielded practically the same value whether it was calculated from a consideration of 15 plots or 75.

RELATION OF SIZE OF SEED TO CROP.

The plots marked *A-I* include the trials of whole sets of different weights. The heaviest "*A*" class consists of seed-tubers of 4 ozs. each in weight. There were five plots of such but only 10 in each, and the p.e. for the mean of five pairs is 10 per cent., which is so high in comparison to that found for the other groups where the plots were 50 tubers strong, as to render comparison of little value. The average crop was actually higher than that of any other seed size, as was to be inferred from previous experience, but owing to the drought of 1921 there was an insufficient number of such sized sets for adequate trials in 1922.

¹ In an experiment on yields now in progress the plots are linear and contain 75 tubers and the replication is tenfold.

Of the tuber-sets corresponding to the weights 2.66 ozs., 2 ozs., .57 ozs. the trials comprised in each case five plots of 50 tubers each, whilst for the tuber-sets, 1.6 ozs., 1.33 ozs., 1 oz., .8 oz., .35 oz. there were in each case eleven plots of 50 tubers each.

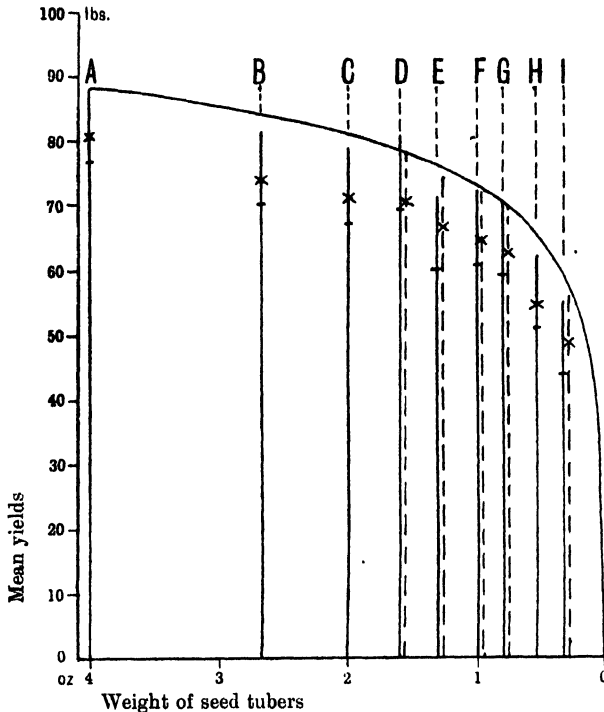


Fig. 6.

The abscissae represent the weight in ounces of the tuber-sets.

The ordinates, the mean yields of the various classes.

The continuous lines represent the mean for fivefold, the discontinuous for elevenfold replications.

The mark \times on each ordinate marks a point equal to $3.8 \times$ the p.e. of the groups B, C, D, E, F, G, H, I replicated five times.

The mark \times marks a point equal to $3.8 \times$ the p.e. of the groups D, E, F, G, I replicated eleven times.

N.B. The yield for "A" is the mean of four instead of five plots of 10 tubers each, one very low value being omitted.

In Fig. 6 the averages are set out graphically as ordinates and the points on the abscissa represent the weights of the individual tuber-set classes A-I. The even fall of yields from the highest to the lowest seed weight class is in accord with previous results.

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The p.e. of the mean of the classes *B-I* for five pairs is 3 lbs., or about 3·8 per cent., and if 3·8 times the p.e. is regarded as a significant difference, then any mean yield which exceeds that of any other class by 11·4 lbs. may be considered to be specifically different, seeing that there is a 30 : 1 chance against the difference being due to a chance fluctuation. On these grounds we can say that the yields of:

Class *B* is significantly higher than that of classes *G*, *H* and *I*.

„ <i>C</i>	„	„	„	„	„	<i>H</i> and <i>I</i> .
„ <i>D</i>	„	„	„	„	„	<i>H</i> and <i>I</i> .
„ <i>E</i>	„	„	„	„	class	<i>I</i> .
„ <i>G</i>	„	„	„	„	„	<i>I</i> .

When the plots *D*, *E*, *F*, *G* and *I* are replicated elevenfold, the p.e. for the mean of eleven pairs is 2·1 lbs., or about 3·0 per cent. of the average yield of the combined plots. In this series a difference of 7·8 lbs. would contribute a significant difference. But no advantage is gained in the order of precedence over that obtained when the plots were repeated but five times, except that classes *D*, *E* and *F* are all significantly superior to *H* as well as to *I*. Had *C* been replicated elevenfold, it doubtless would have then been shown to be significantly superior to *G* as well as *H* and *I*. This can be said with some confidence because the actual means of the fivefold and elevenfold repetitions in *E*, *F*, *G* and *I* hardly differ from each other, nor would there have been any considerable difference between the fivefold and elevenfold means of *D* class, had it not been for one plot of *D* which was abnormally low—unfortunately the fact was not suspected till the raising had been done and the figures were under examination, so that no explanation of this exceptionally low yield is forthcoming. In working out the p.e. this low plot was avoided as far as the tenfold replication and replaced by its average for the elevenfold calculation.

The opportunity was taken of working out the p.e. of plots of *D*, *E*, *F*, *G* and *I* when two neighbouring end on plots were considered together five such plots contained 100 sets. In this trial the row in which the abnormally low *D* plot occurred, was omitted.

The result can be seen in Fig. 7. The improvement as measured by the lowered p.e. is considerable as compared to the fivefold replication of the 50 tuber series, but is as was to be expected, equal to that which would have been obtained by a tenfold repetition of a 50 tuber set plot, involving the same number of tubers but, of course, considerably more labour.

The total yields of the various classes and the p.e. of the difference of their mean when replicated various times is shown in Table V. Here the significant differences between yields are shown in heavy type. Essentially the results are the same and the deductions to be drawn are similar to those in previous years, viz. that with an increase in the weight of the seed-set there is *pari passu* an increase in the total yield and that the difference in yield between the outputs of a set weighing 2.6 ozs. and one of 1 oz. and that between the yield of this latter class and one-half that weight are both real ones.

Table V.

Wt. of tuber set oz.		A	B	C	D	E	F	G	H	I
4.0	A	86	.	- 5	- 7	- 8	-12	-13	-17	-24
2.66	B	81	+ 5	.	- 2	- 3	- 7	- 8	-12	-19
2.0	C	79	+ 7	+ 2	.	- 1	- 5	- 6	-10	-17
1.6	D	78	+ 8	+ 3	+ 1	.	- 4	- 5	- 9	-16
1.3	E	74	+12	+ 7	+ 5	+ 4	.	- 1	- 5	-12
1.0	F	73	+13	+ 8	+ 6	+ 5	+ 1	.	- 4	-11
0.8	G	69	+17	+12	+10	+ 9	+ 5	+ 4	.	- 7
0.57	H	62	+24	+19	+17	+16	+12	+11	+ 7	.
0.35	I	54	+32	+27	+25	+24	+20	+19	+15	+ 8

In this table the yields for *D, E, F, G, H, I* are all averages of 11 replications. In the case of *B, C* and *H*, of 5—as in the case of the *D, E, F, G, H, I* series the mean of the fivefold and elevenfold series was practically identical it has been taken to be so in the case of the other and the significant difference is that found for the elevenfold yields classes *D, E, F, G, H* and *I*.

The yield for “*A*” class has been given as the mean of four more or less equal crops, the fifth an exceptionally low one being omitted.

Perhaps the more important point is that the differences between yields become less as the weight of the sets increases so that the difference between the yields of sets weighing 2.66 ozs. and one weighing 2 ozs. is one that would not be worth the extra price of seed, whereas in the lower weight seed classes the difference in the nature of the crop might compensate for the lower yield. The consideration of this point must, however, be deferred until we have dealt with the analysis of the yields arising from each seed weight class in respect to the quantity of ware versus the quantities of seed sized tubers, and the quantity of chats produced. Before passing on to this consideration a few words may be said as to the seed classes *J, K, L* and *M*. Table VI shows the areas and number of sets involved and the average yields and probable errors. It will be seen that the p.e. is very high in all cases and especially so in the smallest areas so that the deductions to be drawn from these observations are of little or no value.

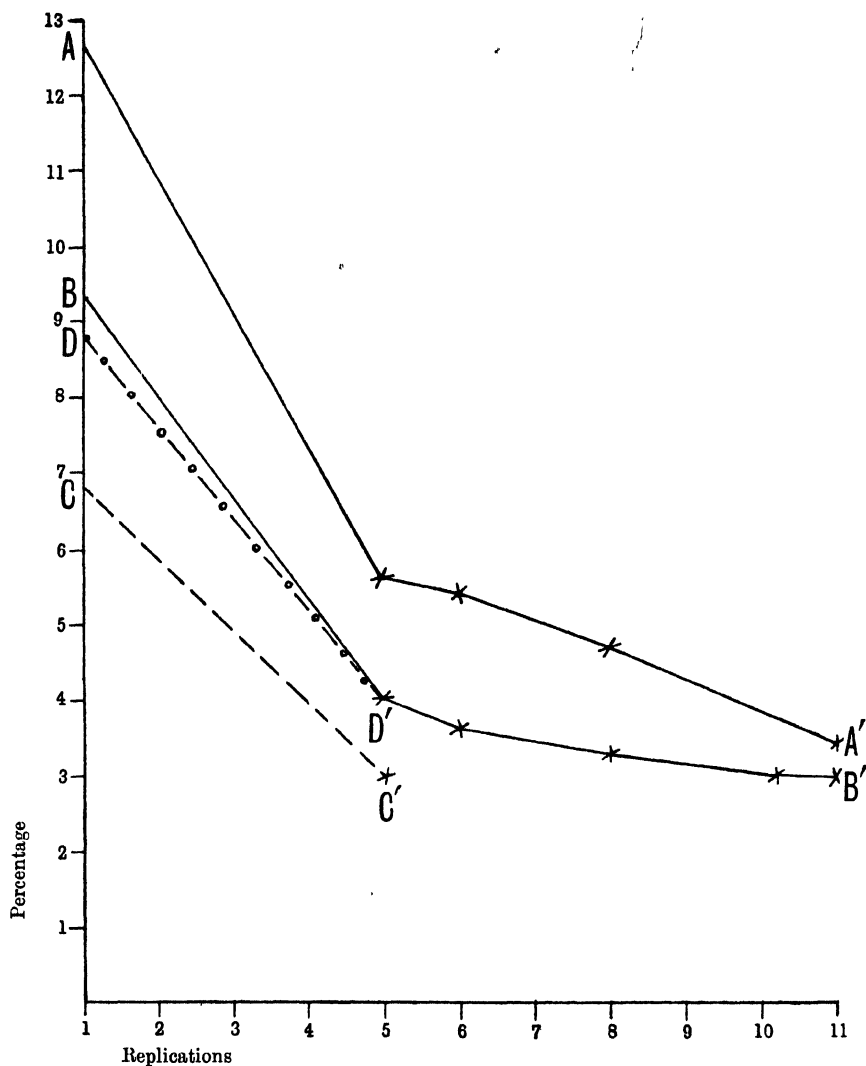


Fig. 7.

Curve A—A' represents the probable error for tuber-set classes *D, E, F, G, I* in which the abnormally low plot of *D* is included, replicated elevenfold.

Curve B—B'. A similar curve excluding the abnormal plot of *D*.

Curve C—C' represents the probable error for the same classes when the plots contain 100 sets on end instead of 50.

Curve D—D' represents the probable error of classes *B, C, D, E, F, G, H* and *I* which are replicated fivefold.

In each case the probable error is expressed as a percentage of the mean of the averages of all the classes *D, E, F, G, I* as present in the 5, 6, 8, 10 and 11 fold trials.

Nevertheless the high yield of class *K*—secondary outgrowths of only .5 oz. weight is in close agreement with the results of earlier experiments on this class of tuber-set and is therefore not without interest. More suggestive, however, is the high yield of class *M*—the heel-ends of tubers. These heel-end sets were severed from the parent tubers immediately before planting, the rose-end sprouts were well grown, whilst those on the heel-end showed no growth. That such basal portions of tubers, though their sprouts be quite ungrown and dormant are valuable as seed, is certainly indicated. The fact indeed may have more scientific than practical value for it not only is in accord with the result of Appleman⁽¹⁾ on potatoes but more particularly with that of J. Loeb⁽²⁾ on *Bryophyllum calycinum* who has shown that apical buds inhibit those below them which intrinsically are as vigorous as themselves.

In the two papers, by the author already referred to, the importance of an analysis of the different weight classes amongst the tubers in the yields from an experiment on seed tuber sizes has been emphasized. In the 1922 results here recorded, the material for examination was far more ample and the results, whilst agreeing completely with those of the previous years, are of a character which makes the conclusions reached of far greater importance.

Ten pound samples from every crop of the series *A-I*, as well as samples of every plot in belt 3 of rows 1-15 inclusive, were carefully analysed into the following classes:

Tubers weighing 3 to 2 lbs.			
„	„	1 „ 1 „	} Heavy ware. (Solid black in diagram.)
„	„	2 „ 1 „	
„	„	3 „ 1 „	
„	„	4 „ 1 „	
„	„	5 „ 1 „	
„	„	6 „ 1 „	} Medium ware. (Cross-hatching, right to left.)
„	„	7 „ 1 „	
„	„	8 „ 1 „	
„	„	9 „ 1 „	} Chats. (Cross-hatching, left to right.)
„	„	10 „ 1 „	
„	„	11 „ 1 „	
„	„	12 „ 1 „	
Tubers weighing under 12 to 1 lb.			

It was found that the production of heavy ware varies inversely as the weight of the tuber set; the relation, however, is not an absolute

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one. The difference between the quantity of tubers weighing 3·2 ozs. and over arising from the heavy seed class *A* (4 ozs.) and the chat class *I* (·35 oz.) is as 50 to 83.

Table VI.

Weight and nature of seed tubers ozs.	Class	Size of plot	No. of sets per plot	No. of plots	Average yield of tubers lbs.	No. of "misses" %	Probable error of mean of 5 pairs %
Whole tuber 4·0	<i>A</i>	10'33	10	5	16·2	18·0	10·0
Outgrowths 1·0	<i>J</i>	10'33	15	5	13·3	19·5	7·0
" 0·5	<i>K</i>	10'33	10	5	13·8	14·0	10·5
" 0·25	<i>L</i>	10'33	10	5	9·0	48·0	16·6
Heel ends 1·75	<i>M</i>	33'70	5	5	16·8	11·2	7·0

The individual variations of value for any one class are not great and the p.e. of the mean of the averages of the heavy ware in 10 lb. samples from each crop is ·42 lb. when five pairs are under consideration and ·25 lb. for the mean of eleven pairs.

In Fig. 8 the various weight classes in each crop are shown and a point is marked in the heavy ware class indicating the value of 3·8 times the p.e., or 1·6 c.c. in the case of five replications and ·9 c.c. in the case of eleven replications.

If we accept a difference equal to 3·8 the p.e. as a significant one, then on the averages from the fivefold replications of the seed classes the following order of precedence in respect to the production of heavy ware emerges.

Class *I* seed weight ·35 oz. is superior to classes *A* and *B*.

" <i>H</i>	"	·55 oz.	} are superior to class <i>A</i> .
" <i>G</i>	"	·8 "	
" <i>F</i>	"	1·0 "	
" <i>E</i>	"	1·33 "	
" <i>D</i>	"	1·6 "	
" <i>C</i>	"	2·0 "	
" <i>B</i>	"	2·6 "	

whilst in respect to those replicated elevenfold a further refinement is possible, viz.:

Class *I* is superior to classes *E*, *D*, *C*, *B* and *A*.

Classes *G*, *F*, *E*, *D* are all superior to classes *A* and *B*.

The results of the 1922 experiment may be also expressed in terms of the net value of the crop. For this purpose the values current before the potato slump of this year are taken. The crop is regarded as one

for consumption and not for further use as seed. All seed tubers used are charged to account at £10 per ton. Heavy ware is valued at £5 per ton. Ware weighing from 3.2 ozs. to 2 ozs. at £2. 10s. per ton, whilst all below is valued as pig food at £1. 10s. per ton.

Making use of these figures, the net value of the crop from each seed weight class has been calculated in pounds and decimals of a pound, as shown in Table VII.

Table VII.

Size of seed ozs.	Total crop in tons	Ware, 3.2 ozs. and over in tons	Value at £5 per ton £	Ware, 3.2 ozs. to 2.0 ozs. in tons	Value at £2. 5s. per ton £	Chats, tubers below 2.0 ozs. in tons	Value at £1. 5s. per ton £	Gross value of crop £	Weight of seed in tons	Cost price at £10 per ton £	Net value of crop £
<i>A</i>	4.0	11.8	6.05	30.25	2.65	6.25	3.1	4.65	41.15	1.8	22.85
<i>B</i>	2.66	11.8	7.7	38.5	2.3	5.75	1.8	2.7	46.95	1.2	34.95
<i>C</i>	2.0	11.5	8.4	42.0	1.4	3.5	1.7	2.55	48.05	0.91	38.95
<i>D</i>	1.6	11.0	8.07	40.35	1.73	4.32	1.2	1.53	46.20	0.73	38.9
<i>E</i>	1.33	10.7	7.8	39.0	1.4	3.5	1.5	2.25	44.75	0.61	38.65
<i>F</i>	1.0	10.6	8.25	41.25	1.2	3.0	1.15	1.72	45.97	0.46	41.37
<i>G</i>	0.8	10.0	8.0	40.0	0.8	2.0	1.2	1.53	43.53	0.36	39.93
<i>H</i>	0.57	9.07	7.2	36.0	0.8	2.0	1.07	1.6	39.6	0.26	37.0
<i>I</i>	0.35	8.3	6.9	34.5	0.7	1.75	0.7	1.05	37.30	0.16	35.7
Unselected seed, rows 1-15, belt 3	11.4	8.4	42.0	1.63	4.05	1.37	2.3	48.35	0.87	8.7	39.65

From this method of estimating the value of particular classes of tuber-sets it would appear that the highest value was rendered by the *F* class = 1.0 oz. set, whilst the lowest is given by the *A* class = 4 oz. set.

It is obvious, however, that these values are subject to the same considerations as regards fluctuations as those for the value of the weights of heavy ware present as well as those for the total crop. For this reason differences in value of crop between £37 and £41 per acre may be probably disregarded as within the limit of a 30 : 1 chance seeing that this value corresponds to about that of 1 ton of mixed crops. This would imply that the best paying crop was derived from seed tubers between the weights of 1 oz. and 2 ozs., that is, of a weight of about 1.5 ozs.

The analyses of the crops of the fivefold series of small plots issuing from the excised outgrowths of large tubers weighing 1 oz. "*J*" and $\frac{1}{2}$ oz. "*K*" respectively, suffered in no way from the small size of the plots as 10 lb. samples were obtainable in all cases, excepting only one instance of "*K*," when but 9 lbs. was available. In the same way, the analyses of the class "*M*," the excised heel-ends, are all strictly comparable to those derived from plots containing a larger number of sets.

The averages of heavy ware in these three classes is as shown in Table VIII.

Table VIII.

Nature and weight of set		Class	Heavy ware
Heel ends	1.75 oz.	<i>M</i>	74 %
Outgrowths	1.0	<i>J</i>	70
"	0.5	<i>K</i>	79

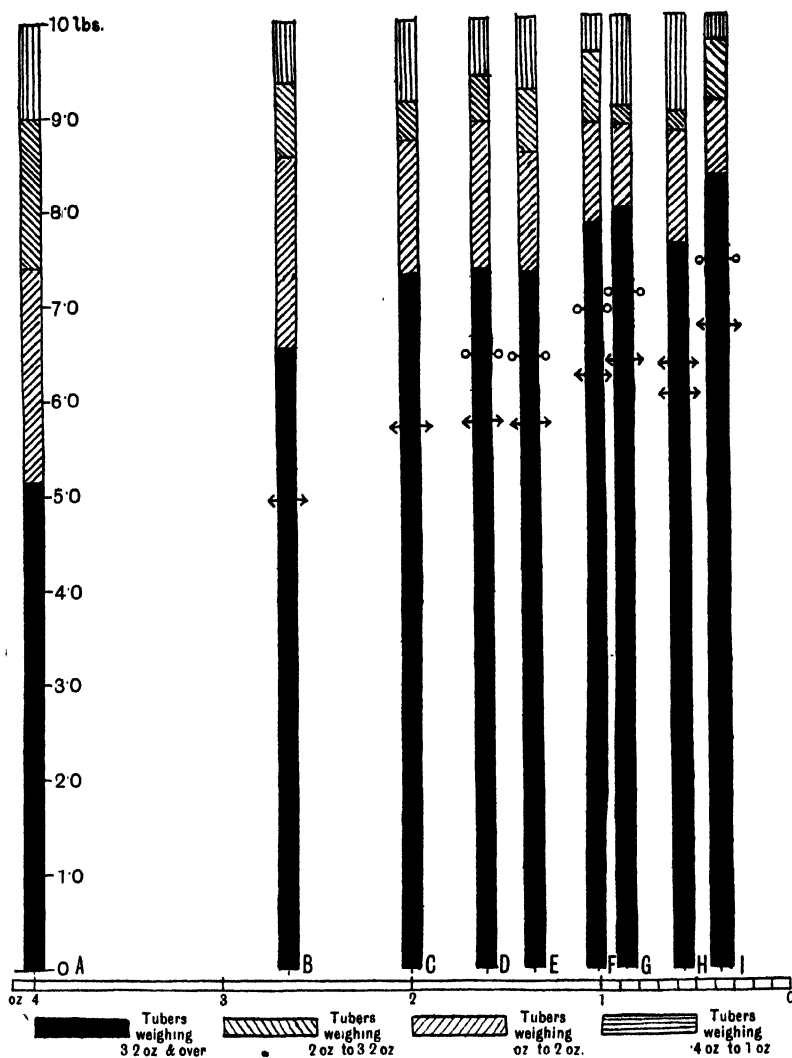


Fig. 8.

↔ Marks off 3.8 times the probable error of the mean of 5 pairs.

○—○ " " " " " 11 "

It is seen that the same weight set, when a cut one, produces a similarly high percentage of heavy ware to a whole small tuber-set and that the actual values coincide very closely with those derived from these latter.

It would thus seem clear that the production of a high percentage of ware is dependent rather on the actual mass of the tuber-set rather than its character. Whether the new plant arises from whole or cut set, whether from normal eye or from outgrowths, whether from apical or basal eye, the controlling factor is the amount of food stuff available in the set for the young plant.

Without attempting to dogmatize as regards the exact weight of the best seed set for the raising of heavy ware, it can, as a result of the 90 careful analyses of yield made from the 1922 crop, be said that the relation of production of heavy ware to size of set is one of the greatest importance and one which most materially affects the ultimate value of the crop to the producer.

The following conclusions may be drawn from the results of the 1922 experiments and the trials of the two previous years.

In respect to yield trial experiments.

1. The number of tubers in a plot should not be less than 50 and need not be more than 100.
2. The number of replications should not be less than five nor need they be more than ten.
3. The size of a plot is determined by the number of tubers contained in it, and if these be planted 1 ft. apart and the rows be 2 ft. 8 ins. apart, a suitable area will be not less than $\frac{1}{3\frac{1}{2}}$ and need be no more than $\frac{1}{1\frac{1}{3}}$ of an acre.
4. The shape of a plot in practice is of far greater importance than its size. Long plots yield far more satisfactory results than short thick ones. This must, however, not be interpreted as implying that the shape in itself is the controlling factor. The reason why the long plot is so markedly superior to the short thick one is because in these experiments the axis of the long plots has been made to coincide with that of the direction of chief soil variation, the existence of which was known from previous experience of the field used.
5. Inasmuch as it is very common for a field to vary in some given direction in respect to its fertility, it is always possible to place the furrows in the direction of the variation and thus exclude its action.

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6. The action of birds (rooks and jackdaws) in rooting out the seed-tubers may produce two results:

(a) A general indiscriminate loss of plants which will not seriously affect the relative yields of the different trials.

(b) Owing to the proximity of roads, buildings, or the presence of workers on neighbouring land, the loss due to this source may take a definite direction.

7. There is a further loss of seed tubers due to the non-growth of virus infected tubers—this loss occurs practically exclusively in classes of seed tubers weighing less than 1 oz. and produces a variation which may enhance or decrease that due to soil change or other cause.

In respect to seed tuber size, and its relation to the yield.

1. The larger the seed tubers the greater the gross crop they produce.

2. The size of the gross crop diminishes with the diminution of the size of the seed tuber, at first gradually, then more rapidly.

3. The proportion of useful heavy ware in a crop bears a very definite and close inverse relation to the weight of the seed tuber.

4. In estimating the monetary value of a crop this relation is of great importance, as is also the money spent per ton on seed.

5. As a result of the above it does not follow that the heaviest seed produces the most valuable crop. On the contrary the highest net return actually obtained was from seed weighing 1 oz.

6. Allowing for the variation—which is not high—of the ware production of any given class as well as that of the gross crop, it may be taken that a seed weight of about 1.5 ozs. is the best for the production of a crop of the highest monetary value.

7. It has been shown that seed tubers of a lesser weight than 1 oz. selected from a general crop will be undoubtedly more highly infected with virus diseases—presuming these to have been present in the parent stock—and that tubers of 1.3 ozs. to 1 oz. weight may be considered to be to a lesser degree suspect. The seed tuber in general should therefore not weigh less than 1.5 ozs.

8. Cut sets produce the same ratio of heavy ware as whole sets of corresponding weight.

9. Small sets derived from the outgrowths of large tubers are less likely to be infected with virus diseases and the gross output of such sets has in previous years been shown to be exceptionally high.

In conclusion it should be stated that while the results recorded, though clearly to be deduced from the material experimented on, are not

stated as being true for varieties other than the one here used, viz. Barley Bounty, nevertheless it is highly probable that they have a general application in respect to potatoes.

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INVESTIGATIONS ON YIELD IN THE CEREALS¹. I.

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(With Plate IV and Two Text-figures:)

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PART I.

GENERAL CONSIDERATIONS.

It is unlikely that as a formulated problem any consideration of settled crop-husbandry is of greater antiquity than the cereal yield problem. In its broad form it embraces all the possible means of increasing the output of grain per unit area. The earliest civilizations of Mesopotamia and Egypt must have been compelled to explore these means as soon as they began to encounter the limitations to cultivable area which dwelling in fixed communities imposed. Wheat and barley were their principal food

¹ This paper will be completed in the next three numbers of this *Journal*. In each number a complete bibliography will be given but of the Tables only those concerned will be published.

stuffs so that the cereal yield problem, the most comprehensive concern of present-day agriculture, goes back to the remotest antiquity. It must have evoked incessant effort along divers lines and the cumulative result is appreciable from a comparison of the best cereal races of to-day and the forms which like *Hordeum spontaneum* and *Triticum dicoccum dicoccoides* have been regarded as the progenitor types. Unfortunately it is not possible to trace back very far the sequence of the solution of the problem as constituted by improvements in husbandry and the utilization of better cereal forms. Fragments of information may be culled from the writings of various periods but they are of doubtful value. The author's reliability is often in question, the unit of measure uncertain, and even the identity of the crop a matter of doubt. Herodotus' well-known story, passed on from another, of increases of 200 and even 300 fold yielded by barley in Mesopotamia in 500 B.C. is possibly the oldest fragment. It is difficult to interpret but it gains colour from the further statement that the leaves of the plant were of the width of four fingers. Concerning progress in England, while reasonably precise information goes back no further than forty years, there are widely separated records of sufficient worth to indicate the historical trend. It has been deduced from the Manorial Records that at the time when that system had become established there was a flat rate of about ten bushels per acre for wheat. Much later, when Sir Charles Davenant compiled *An Essay upon the Probable Methods of making a People Gainers in the Ballance of Trade* (published 1699), he computed the "neat produce" of eight million acres of arable land to be 79 million bushels of grain. Adding to this 11 million bushels for seed, the gross produce is 90 million bushels or an average yield of 11.2 bushels per acre. The total yield includes beans, peas, and vetches (12 million bushels), and the four English cereals (67 million bushels). If these estimates are at all reliable there can have been only a small augmentation of yield in some three hundred years. Onwards from the end of the eighteenth century records are far more numerous and more reliable. Major P. G. Craigie read before the Statistical Society in 1883 a paper entitled "Statistics of Agricultural Production." In this he collected a series of ten estimates of yield the first being that of Arthur Young in 1770 and the last the *Inquiry of the Farmer and Chamber of Agricultural Journal* for 1882 and the two preceding decades. Arthur Young's figures for wheat in the separate counties include values from 31 to 18 bushels per acre and 23 bushels was his estimate of the average for the whole country in 1770. These figures certainly cast a curious light on the estimates of Sir Charles

Davenant who drew upon the computations of Gregory King, but it is interesting to note that whereas Arthur Young estimated the area of England and Wales to be about 47 million acres, Gregory King's estimate was 39 millions (the actual area being, of course, about 37 millions). In the intervening estimates very varying figures are disclosed and the last of the series shows, for wheat in the separate counties for the period 1863-82, yields of from 40.6 to 26.6 bushels per acre. Major Craigie discoursed very fully upon the probability of the different estimates and made clear their limitations. But perhaps it is a justifiable conclusion from the data he furnishes that between 1770 (Arthur Young) and 1850-1 (Caird's comprehensive data in his *English Agriculture in 1850-1*) there was a steady rise in cereal yield in England which was continued to 1882, the date of the last estimate. From 1883, the year in which the Board of Agriculture took over from the Board of Trade Officers the collection of Agricultural Statistics, much more comprehensive and reliable data are available. An examination of these makes it appear that cereal yield in the 38 years covered by the Statistics has not increased in any very noteworthy way. In Part II of the *Agricultural Statistics* for 1907 are graphic presentations of the fluctuations in yield per acre of the cereal crop for the preceding 20 years. The curves are very irregular but oats, and to a less extent wheat, shows a slight rise while barley fluctuates about a level. From 1907 to 1921 the indications of increase are no more emphatic. This meagre inquiry into a great and difficult subject may perhaps be considered to indicate that cereal yield in England has slowly but definitely risen but that the tendency to further rise has for the past forty years not been strong. Since in this time, whatever can be said for the farmers of the past, land and practice cannot have deteriorated very sadly in general, it is indicated that no very striking success has attended the plentiful efforts to increase yield by the growing of improved varieties. Positive conclusions on this matter are, of course, dangerous, but the facts do at any rate emphasise the extreme difficulty of raising cereal yield in England. Continued improvement must be expected to demand the most elaborate investigation.

Cereal yield is controlled by a great number of factors which are themselves complex and imperfectly understood. In approaching the "yield problem" it is convenient to arrange these in broad categories which may thus be designated: (i) Soil, (ii) Climate, (iii) Agricultural Practice, (iv) Disease and Damage, (v) Botanical variety or form.

Categories (i) and (ii), though beyond control, are relevant to the problem in an interesting way. No variety can be expected to surpass

all others in every locality of the country. That some display a marked "adaptation" to certain localities is well known and it is clear that an advance could be effected if, for every locality, the best adapted variety could be determined. Adaptation is a phenomenon of obscure nature but its manifestations are in some instances so marked as to suggest that possibly the selection of the best form for every locality would be the most important step of immediate practicability in the solution of the "yield problem." Accumulated farming experience will, in time, produce a verdict upon the adaptability of any variety, provided nothing occurs to oust it before it has had a fair trial. But new varieties are ever being thrust upon the notice of the farmer by lively propagandists: and before he has properly tested one form, half a dozen new ones have been offered. To grow a new form on field scale is necessarily somewhat speculative. Looking over the long list of forms marketed, advertised, grown by farmers and then, shortly, abandoned, there arises the impression that some farmers must have suffered in yielding to the attractions of "novelties." Many forms have been tried in localities to which they were entirely unadapted and the need for the machinery of preliminary locality trials is quite apparent. Such trials do not offer the full solution. Ideally, attempts should be made to interpret "adaptation" in biological terms. These would have to take the form of investigations into the responses of cereal forms to environmental factors. A pattern for such experiment is afforded by the striking "analysis of yield" commenced by Balls and Holton and completed by Balls for cotton in Egypt. But irregularity of rainfall and sunshine and the acute general inter-seasonal differences so characteristic of England, would place great difficulties in the way of such experiments. And again, the cereal plant, in a sense a colony of individuals (tillers) rather than a unit, is not yet sufficiently understood to permit of the analysis of its yield in terms of the stages of development of the plant. For these reasons it has appeared undesirable as yet to attempt to investigate this most important phenomenon of adaptation. A preliminary investigation of the characters of the cereal plant seemed the first practicable step and Part II describes some work done in this connection. It may, however, be remarked that valuable evidence upon adaptation might be obtained if some of the bigger seedsmen would digest the records of growing of the different varieties over the large areas which they serve. Study of the Correlation of the Crops and the Weather, etc., though so wide that it cannot give other than very general indications, is certain to be of value. Progress is steadily being made as may be seen in the writings upon this subject of Hooker (*Journ. Roy.*

Stat. Soc. **70**, 1907, and *Q. Journ. Roy. Meteorol. Soc.* **48**, 1922), Hall and Russell (*Journ. Bd. Agric.* **17**, 1910–11), Fisher (*Journ. Agric. Sci.* **11**, 1921), and Geddes (*Journ. Roy. Meteorol. Soc.* **48**, 1922). The results can go no further than to characterise the main cereal groups—wheat, oats, and barley—but they will be a guide and a stimulus to varietal studies of adaptation within the group.

The next factorial category [(iii) Agricultural Practice] may safely be relegated to the farmer. Some recent innovations are noteworthy, particularly the light regular seeding and surface sowing which are at present under trial. Both these procedures bear very directly upon known habits of growth of the cereal plant and it seems certain that *ad hoc* experiments would usefully amplify the field tests.

Disease and damage, the fourth category of yield-controlling factor, give rise to many interesting considerations. Actually they pertain to category (v), (variety or form), for they are best overcome by the raising of immune varieties rather than by "treatment." Of the diseases, yellow rust (*Puccinia glumarum*), smuts and bunts (*Ustilagineae*), leaf-stripe (*Helminthosporium gramineum* Eriksson) and mildew (*Erysiphe graminis*) are the chief fungoid forms while wire-worm, frit-fly and eel-worm are the worst of the zoological pests. Cereal forms resistant to yellow rust can, as the work of Biffen shows, be "bred to order." There is a mildew-resistant wheat (Persian Black), Gaines⁽⁵³⁾ has made progress in tracing the inheritance of resistance to "bunt" in wheat and there are even indications of an ordered heritability of eel-worm susceptibility. These and several other similar facts hold promise of great ultimate advances in the breeding of resistant forms. "Damage" by lodging, the breaking-off of the ripe ear, grain shedding, grain "sprouting" and numerous other processes, is very familiar. Liability to damage in most of its forms is sharply varietal and there are many examples of its elimination by hybridizing of otherwise desirable character combinations. Immunity to damage and disease is probably the most straightforward line of advance in producing higher yielding forms. It is a distinct department and its results will naturally reinforce whatever progress is made in other ways. The considerations which follow take no further account of this aspect.

Botanical form, or variety, is the remaining category of yield-controlling factor. Endless new forms can be produced and some of them ought to be better than existing forms. The problem is to make sure of choosing the best. Diverging for a brief space from this problem, attention may be given to the methods of obtaining new varieties. "New" is

here to imply "not in cultivation in England" and there are three methods: (i) Selection, (ii) the Introduction of Forms from Other Countries, (iii) Hybridization.

Every field crop of a cereal contains "rogues" or plants differing from the bulk. It is an old and favourite practice to "select" these in the hope of securing valuable forms. Rogues may be of various origins. Seed of other established forms or of foreign forms may become admixed to a bulk of seed; or to a limited extent natural cross pollination may produce rogues: and if every theoretical possibility is to be accepted, rogues may be "mutations." Rogues selected from fields or found in waste places have been the progenitors of some valuable English forms included in which are Chevallier barley, the Sandy oat and the Potato oat. Of their botanical origin nothing is known. A constant watchfulness for valuable rogues has a great fascination and may yet again be repaid. The introduction of forms from other countries has not profited England very greatly. The old native races of the East and of Africa fail dismally as field crops though a small number promise to be valuable as parents in hybridization. Such as the Victory oat and Iron wheat are simply hybrids raised by foreign plant breeders. The former has been an emphatic success while the latter, though yielding well, but serves to deteriorate the already low baking quality of the English wheat output. Hybridization is naturally the most prolific of the methods of obtaining new cereal forms. In the barleys inter-specific crosses of all sorts are fully fertile; in the wheats there is sterility in such crosses though save in the case of *Triticum monococcum* it does not entirely prohibit desirable hybridizations; in the oats there are almost certainly some sharp limitations but their extent is not yet known. Thus the scope of plant breeding in the cereals is very wide indeed. The last fifteen to twenty years has brought method into what was formerly a speculative procedure. For long the hope was cherished that from crosses of widely different parents, especially if they were in some respect unusual forms, there would result valuable novelties. Experience showed that the whole novelty lay almost invariably in external morphology. Later workers carefully selected their parent forms on account of some proven desirable character. This change in procedure was important and its results have been very considerable. It was largely to the discovery to the world at large of Mendel's "Laws," of the idea of segregating "unit" characters, that the altered procedure was attributable. The discovery certainly stimulated afresh the art of plant hybridization in general. That agriculture has benefited immensely from the work of hybridists is too well known to call for any mention

of specific instances but the future prospect opens up the essentials of the "yield problem."

From this point of view the possibilities of solving the problem may most conveniently be approached by considering the plant-breeding procedure which has been so fruitful and to which no alternative yet exists. Two suitable parents are crossed and the resulting F_1 plants, self fertilizing, produce an F_2 generation the customary size of which is 400-600 plants. The number of different types it contains depends upon the extent of the genetic difference between the parents. With experience, it is usually possible to reject some of the F_2 plants as useless *e.g.* on the ground of excessively long and weak straw, etc. Let it be supposed that 300 F_2 plants are kept, giving in the year following, as many F_3 families with an average of 40 plants per family. It will be obvious that in some families there are different types of plant; in a few, no differences are apparent. Families of the latter kind may be regarded as "fixed" or homozygous. To grow them on complete involves the risk of accepting as fixed a population which, as a fact, is heterozygous in regard to one or more obscure but possibly important characters. To improve the chance of obtaining uniformity it is desirable to extract from the F_3 families of all kinds, none but single plants. In doing this experience must again be the guide unless $300 \times 40 = 12,000$ single plant cultures are to be raised as an F_4 . This reliance on experience for the selection of, say, 1000 plants from a total of 12,000 is commonly known as "eye-judgment." Propagation is continued on these lines and by F_8 to F_{15} there may be some 30 cultures each of, say, 25,000 plants and each, as far as the eye can tell, homozygous in regard to every character. For security it should be a rigid rule that at the least indication of non-fixity of type in a culture, there should be an immediate return to single plants. This stage having been reached, drastic selection of the "best" by eye-judgment has to be practised. Of the 30 cultures some 5 or 6 are chosen and chess-board trials of yield are made. One or possibly two of the new forms are carried on from these trials to field testing, and, possibly, to the market. Despite the rejection of so high a proportion of the possible total of cultures, a procedure of the kind outlined involves a laborious routine. Such is inevitable, but drastic reductions in every season are imperative unless there is unlimited assistance and financial resource. In principle the treatment of "selections" (rogues) from field crops, etc., is precisely similar and the problem can be adequately discussed by confining attention to hybrid progenies.

There are opponents of the "eye-judgment" procedure described

above: but before probing the alternatives which they favour, it is desirable to dwell briefly upon the nature of eye-judgment. It is not infrequently described as "guessing." Whether or not this charge lies, must depend largely upon the experimenter. Anyone who allows himself to be deceived by the characteristic robustness of the plants on the outside of a plot or in any comparable manner is, of course, not merely guessing but systematically pursuing the wrong line. And again, the most striking plants in a culture are frequently those which may be known, from experience, to be heterozygous. A good example is to be found in segregates from the cross of a 6-row and a 2-row barley which are heterozygous in regard to their lateral florets. Neglect of indications of heterozygosity may result in the selection, year after year, of the "splitting" forms and disappointment at the impossibility of "fixing" an attractive type. The employment of "eye-judgment" implies the full utilisation of everything that is known concerning the mode of inheritance of the characters involved as well as allowances for the known effects of ample soil space, etc. But eye-judgment has to cope with other matters as well. Length and strength of straw, brittleness of rachis, susceptibility to disease and the like, are blemishes detectable with practice and justifications for rejection of cultures in the earliest stages. The crux of the whole matter, however, is to tell by eye which forms will be the heaviest yielders. It is the attempt to do this that principally evokes the charge of "guessing." And yet experience, supported by some notable achievements, indicates that the eye can become trained to this difficult work. No cereal form yields well which does not possess "tillering power" of a fairly high order; but of itself, number of tillers formed is no guarantee of yield. There must be a reasonable number of side tillers produced soon after the main axis and developing ears not markedly smaller than that of the main axis if a heavy crop is to be obtained. With the characters of the ear, too, there are certain essentials. The long, spindly, ear in wheat with few grains (*e.g.* twos and threes) per spikelet has never yet characterised a high-yielding form although it may give an attractive appearance to a plot. Broad judgment on ear-form is thus not entirely "guessing." Perhaps the general basis of eye-judgment is, more than anything else, the estimation of the number of grains per unit area, the "density" of grains on the "top" of the area. Special considerations are called for in almost every individual cross and it need occasion no more surprise that the "eye" of some observers can become trained to judgment of this kind than that the miller, the maltster, the wool-sorter and others, base their important decisions largely upon "appearance."

The alternative to eye-judgment must now be discussed. In principle it is exceedingly simple. Every plant raised from a cross would be grown on. As long as segregation continued single plants would be kept separate in every generation. Segregation would be determined by the eye—there is no suggested alternative to this. When sufficiently large stocks of apparently “fixed” types had been accumulated, chess-board trials would be made and by degrees the best forms be brought to the market. It is argued first that only by growing on every type can one be certain of not rejecting valuable forms; and next that two or more plants, alike to the eye, may be of different genetic constitutions and *ipso facto* of very different yielding powers. These are irrefutable arguments and in theory the idea of growing on every plant is unassailable. But in practice it might involve a chess-board of say at least 1000 forms from a single cross. Such a yield test would cover an area of over seven acres the whole of which ought to be enclosed in the usual wire “cage.” While the products of a single cross were being dealt with in this way, those of at least thirty crosses could be handled by the customary judicious employment of “eye-judgment.” And when the diversity of the localities of England is borne in mind, the need is seen to exist for the breeding of cereal forms of many types and of many different parentages. It has seemed desirable to explore the requirements of a theoretical method, frequently advocated, in order to assess the great economy of working which the existing procedure secures.

The keenest advocate of eye-judgment cannot deny its numerous defects. Some more systematic index to yielding-power applicable to small populations of plants, is manifestly much to be desired. A “touchstone” is required to regularise preliminary selection for yield among the numerous forms resulting from a cross. Many endeavours have been made to find in the external morphology of the plant some index to yielding power. Broad features such as a long, dense, ear with many grains per spikelet in wheat are helpful, but a more discriminating form of index is necessary. Morphological features have failed to provide such a guide and attention has therefore been directed to length and weight characteristics. In one case only has there been any indication of success. Dr E. S. Beavan of Warminster has employed the “migration coefficient” which he defines as the proportion by weight of grain to total produce. He finds that, as between different forms of barley, the relative magnitude of the coefficient is an index to the relative yielding power. The use of this coefficient is simpler than such trial methods as the “chess-board” but it is too laborious to be regarded as the “touchstone” which is so much needed in breeding cereals of high yield. Though this index is in-

applicable to very small plant populations its further study is extremely desirable. Possibly a really simple index to yielding power is not to be hoped for: but simplification is so vital a need that further search seems necessary. The outstanding feature of the whole question is the lack of knowledge concerning the salient "characters" of the cereal plant. In these must be sought an index of the desired kind so that the first step appears to be a study of the attributes or characters of the cereal plant, a matter which comes again under consideration in what follows.

Many times the question has been asked "Is yielding capacity heritable?" The answer has been afforded by actual plant breeding achievements. For example, a high-yielding wheat of good baking quality has been bred from two parents each of which possessed but one of this pair of desirable attributes. This is one of a number of answers to the question—it is, perhaps, the cleanest cut example. In a broad sense, yielding capacity (very high capacity as distinct from very low) has certainly been shown to be heritable. But the question is worthy of closer consideration. Those by whom it has been asked are persuaded that the commonly recognised "plant characters" are all regularly inherited whether of the kind conveniently called morphological or physiological. Their question, then, ought really to be paraphrased and "Is yielding capacity an attribute expressible in terms of plant characters?" may perhaps be suggested as a better form. In regard to extremes of yielding capacity, actual results offer an affirmative answer to this altered form of the question. But it may well be that a slight difference is so much at the mercy of precise environment that it cannot be described as of the nature of a plant character. Experience shows that improvements in yield by the raising of new varieties, are obtained very gradually, by steps of perhaps, some 2-5 per cent. This being the case, it is a matter of the greatest importance to interpret yield in biological terms for only in these, can accurate experiment be made.

The importance of an interpretation is best seen in the full comprehensive proposition for solving the yield problem by raising new hybrid forms. Theoretically the procedure should be to find out the plant characters which control yield per acre and by a synthetic system of hybridizations to accumulate into one plant-form the optimum combination of yield-controlling factors. The optimum combination would doubtless be different for different localities and seasons, a fact which causes attention to revert to the "adaptation" problem already discussed. And again, it may be that the best existing forms already

embody the optimum combinations for a succession of seasons and thus that owing to the vagaries of the climate, no further improvement can be wrought by raising new forms. Only by resolving the cumbersome but economic "attribute" of yield into biological characters can these doubts be probed. The procedure for this seems to be a determination of the relation of all acceptable "plant characters" to yield and of their inter-relations. To carry out the full project for increasing yield by plant-breeding, such determinations would have to be followed by investigations of the mode of inheritance of the characters which proved to be related to "yield" in order that hybridization might proceed on definite constructive lines. Here then is an experimental scheme.

Now experiment cannot proceed on a "per acre" basis for observations on plant characters must be made with the single plant as a unit. At the same time, crops have to be grown by the acre and therefore a bridge must be found between the single plant of the experimentalist and the field crop of the farmer. A field crop is a population of single plants enjoying different environments. Soil and cultural differences characterise these environments, but this is equally the case in the experimental plot. The outstanding difference of single-plant environments in the field is the spacing. As an insurance against loss by wire-worm, frit-fly, etc., the farmer always sows an excess of seed. Of the total sown, only from a quarter to a seventh grow into mature plants. The losses are irregularly distributed so that many different spatial arrangements pertain in a field. Thus the behaviour of a cereal form at a variety of spacings is a very important feature of its "field behaviour," of its yielding capacity per acre. This feature indeed seems to be the bridge between accurate experiment and agricultural practice. All relations between yield per plant and other plant characters must be tested at a variety of spacings and clearly it would be of great advantage if some knowledge could be gained of the distribution of the spatial interval over ordinary field crops. To yield well, a variety must be able to withstand some degree of crowding, must grow well at the most prevalent spacing, and in the thinner parts of the field must respond to liberal soil space sufficiently to compensate for the reduced number of plants per unit area.

For the prosecution of the investigation the following thus seem to be required:

- (i) To determine the relations to yield per plant of other plant characters (some or all of which may be presumed to be "components" or governing factors of yield).

(ii) To find out the mode of inheritance of those characters which are components of yield.

(iii) To test all relationship at a succession of spacings.

An investigation of this kind can deal only with characters of the plant which lend themselves readily to metrical representation. And of these it is impracticable to observe more than a limited number. To select those which seem likely to be related to "yield" is naturally indicated. The best guide to selection seems to be a simple algebraic analysis of the average yield per plant for a population. This average may be represented as the product of:

Average number of ear-bearing tillers per plant.

Average number of grains per ear.

Average weight of a single grain.

Average percentage of dry matter in the grain.

There is abundant evidence that these average values are extremely fluctuable and that they are inter-related. But the exact nature of the fluctuations and of the relationships is not known and thus the practicability of these average values as experimental variables is quite uncertain. Thus even for a single variety it is quite impossible at present to interpret yield per plant in terms of components. Until this has been achieved, inter-varietal comparisons are out of the question and there is no prospect of transmuting elementary algebra into constructive analysis.

The cereal plant, a colony of tillers of different ages and sizes, is a cumbersome unit of observation. That broad relationships subsist among the attributes of the tillers is well known. The main axis is usually bigger in all respects than the first side tiller which, in turn, is bigger than the second, *et seq.* But of the constancy of the relationship of their sizes nothing definite is known. The form of the relationship is different in different varieties—particularly perhaps in the oat—but here again knowledge is too general to have any analytical value.

The central variable of these considerations—yield of grain per plant—is itself complex even in a mechanical sense. It is composed of water, of "husk" (oats and barley), and of a complicated balance which is useful as food. Possibly in estimating yield for experimental purposes dry weight, or weight of starch, or some other corrected form of "weight of grain" would rid observation of part of the troublesome fluctuation familiar in yield studies.

It is seen that the prosecution of the comprehensive proposition of "synthesising" high-yielding forms is arrested by a lack of knowledge of the characters of the cereal plant. Past experience suggests the in-

advisability of elaborate studies of yield analysis as a means towards the final synthesis until a preliminary exploration of some of the salient plant characters has been made. For this reason the undertaking described in Part II has taken the form of a general reconnaissance rather than that of an *ad hoc* experiment.

From a miscellaneous body of not very precise evidence as well as on general principles,* it is concluded that the root system is intimately related to yielding capacity. Conceivably two desirable features of the aerial part may be united in a new form by crossing, *e.g.*, high tillering from one parent and numerous grains per ear from the other. The combination represents a potentiality for increased yield but if the parents both have a root system adequate only to their own aerial parts, the new potentially valuable form may have a root system which is unable to meet the full demands of the increased capacity ensured by numerous tillers bearing many grains. Like most other inferences as to the cereal root system, this is purely speculative, but it is clear that in yield studies the root system cannot be neglected. Rate of increase of dry weight throughout life and the precise details of time of flowering are similarly possible partial indices to yielding power.

One interesting and delicate aspect of the yield problem in its broad sense is the phenomenon of synonymy. It is notorious that some varieties are sold under several different names. No one likes to risk the consequences of publishing a "list of synonyms" but such a thing would be of value to agriculture. For a farmer may try a form of wheat, and finding it of no use to him, give it up; then five years later he is persuaded to buy it under a new name and to bear, once more, the expense of testing it. In some cases dishonesty, and in some error, is responsible for the creation of synonyms but at present no methods exist for positively testing doubtful cases. Some of the characters of the juvenile plant—coleoptile, first green leaf, early tillering, etc.—appear to lend themselves to diagnostic work of this kind. For this reason the observation of some of these characters has been included in the investigation described in Part II. Quite possibly dry-weight development and time of flowering (the precise data) might serve to the same end.

Investigations upon metrical characters of cereal plants have always presented great difficulty on account of the range of fluctuation which is always encountered. Precautions in sowing and in drawing the experimental sample may lessen the range but they add to the labour. For guidance in further studies it is desirable to ascertain the value of various possible precautions as well as the size of sample required to

ensure any specified degree of reliability of results. These matters were brought within the scope of the series of investigations which is to be described.

The actual ground covered by the investigation may be readily seen from the list of contents of Part II which follows. A procedure such as the weighing of the individual grains of an ear may appear supererogatory but lack of information on matters of troublesome detail is, in the present state of knowledge, the immediate bar to progress in the analysis of yield. Two-row barley was selected as the experimental plant because of the comparative uniformity of its grain weight and also, since it is a spring-sown crop, the observation period does not include the really bad weather which renders detailed observations in the field so arduous. Two pure lines of barley were investigated, the one of Plumage and the other of Archer. Both are among the best yielding forms. By selecting two forms of very different yielding powers an atmosphere of finality might have attached to the results because of the magnitude of inter-varietal difference which would have been exposed. But the object was to explore possibilities, and reliable pure lines of these two varieties were obtainable. Moreover results for one variety with a pair so comparable in period of growth and final produce, may be used as a general check against those for the other. Emphasis is once more laid upon the fact that the present state of knowledge does not permit of direct attempts to resolve yield into its components but rather necessitates a thorough general reconnaissance of the characters of the cereal plant. Relevant literature has been briefly reviewed to obtain comparative evidence and considerable weight has been placed upon that afforded by genetic evidence, for the ideal final "synthesis" of forms of superior yielding capacity is a problem of applied genetics. The purely statistical basis of this investigation appears to call for little apology. To plant physiology we must look for the final solution of the "yield problem" but meantime for plant breeding the only practicable course is to seek an advance by investigation of the statistical characters which are more amenable to observation than those in terms of which physiology has to proceed.

PART II.

A STUDY OF CERTAIN BARLEY CHARACTERS: METHODS, FLUCTUATIONS, AND COMPARATIVE OBSERVATIONS ON TWO PURE LINES.

§ I. MATERIAL AND METHOD.

The familiar agricultural varieties Plumage and Archer were used, the stocks being old and very carefully kept pure lines. In 1919 they were raised in ordinary experimental plots. For various purposes in 1920, they were grown in water culture, in sand, in deep trenches filled with sifted soil, in flower pots, and, to maintain stocks of seed, in ordinary plots as well. Most of the results to be recorded are from the 1921 growing and this must be described in detail.

Table XII affords a ground plan. The four double columns represent four beds (Nos. 5-8) in a "cage," half of each bed being sown with Plumage (denoted hereinafter by *P*) and half with Archer (*A*). The rows were at right angles to the long sides of the beds and were 1 foot apart. In Beds 5 and 6 the plant-to-plant interval in the row was 4 inches; in Beds 7 and 8 it was 2 inches. Every bed contained 26 rows of plants of each variety, there being 23 plants in the row for the 2-inch spacing and 12 for the 4-inch. Thus, for each variety, there were two sets each of 598 plants for the 2-inch spacing and two each of 312 plants for the 4-inch.

It had transpired from some of the 1920 investigations that the very considerable labour required to secure for sowing seeds of practically uniform weight, was not justified by results [see also (1)]. Consequently seed was selected by picking out from a big bulk, sound, perfectly matured ears of the "modal" type, this type being decided upon by a count of the number of grains per ear throughout the bulk. From every ear so selected there were taken the best five grains from each side of the rachis, and these grains were finally examined to exclude any which showed signs of damage or other defect.

Sowing took place on 14. iii. 21. The ground had been carefully dug over and raked smooth and the ordinary dibbing-iron was employed. Wheat, dibbed at regular intervals, had occupied the ground in 1920. Two papers by Kulkarni (2) and (3) had suggested the desirability of putting seed in the ground "the right way up," but this precaution was not taken because trial had shown that it was needless. [See Appendix I.]

There were casualties among the plants. Germination was good but various pests—in particular wire-worm—took a heavy toll. To secure

as great uniformity as possible, every plant was excluded from counts of tillering, etc., which could be observed to have had a "non-uniform" environment. The two neighbours of a dead plant, "outside" plants of every row, plants injured by caterpillars eating the leaves, etc., were thus excluded. Exclusion was determined by the results of periodic plant-by-plant inspections and it resulted, as the totals in the tables show, in wholesale reduction of the numbers of plants available for numerical data. Part of the purpose of the investigation was to test the practicability and value of working only with plants grown as uniformly as was possible and for this reason it was decided to employ the limited numbers available rather than to increase the observations by accepting obviously objectionable plants.

Observations were made upon time of flowering and special precautions were taken in harvesting but these need no further reference at present. At weekly intervals plants were lifted from the 2-inch space sowings for determinations on dry weight, nitrogen content, and ash content. These liftings further reduced the numbers of plants available for observation. [The numbers in the tables will be seen to become less.]

This ample account of material and method has been written for the reason that the graminaceous plant with its habit of "tillering," offers very great difficulties to quantitative investigation, and it appears to be of first importance to gain an idea of the degree of uniformity which can be secured by full precautions.

Throughout, the word "germination" is used in its popular acceptance, *i.e.* appearance of the plumule above the soil. Precise definitions, *e.g.* emergence of the radicle are open to question and cannot be applied to seeds sown in soil.

§ II. THE COMMONLY ACCEPTED DIFFERENCES BETWEEN THE TWO PURE LINES.

Plumage and Archer barleys are very familiar in English agriculture. In appearance they are obviously different and certain cultural distinctions have manifested themselves.

The commonly accepted differences are:

Ear—*P* is broader, *i.e.* has shorter rachis segments.

Grain—*P* is of greater circumference and has the basal "ridge" which characterises many broad-eared forms of *H. distichum*. An inconstant development of purple pigment in the paleae, observable in both, is usually the more marked in *A*.

Straw—*A* is shorter than *P* and the "neck" (top internode of the stem) is straighter. There is also a greater development of sclerenchyma in *A* to which is due, no doubt, its greater strength.

Tillering—*A* is usually considered to tiller more freely than *P*.

Root—The root system in the young plant is the more extensive in *A*.

Germination—On the malting floor *A* is the slower.

Growth Period—In general, this is slightly longer for *A* (growth-period = sowing to harvest).

Yield—In most localities *A* slightly out-yields *P*.

Quality—For malting purposes *P* is rather the better.

Soil—On poor soils *A* is distinctly more successful than *P*.

Farmer, maltster and plant breeder have studied these two barleys very carefully and in relation to their efforts the list of differences may appear somewhat slender. But it is doubtful whether a much more comprehensive schedule could be drawn up for two comparable forms of any other farm crop. To supplement this list has been one of the objects of investigation.

§ III. FIELD NOTES ON GROWTH IN 1921.

Development was studied by weekly observations of dry weight per plant, etc., and it was thought that interest would be added to the results—and perhaps their interpretation facilitated—if regular field-notes on growth were made. Accordingly, on the days when sample plants were lifted, such notes were written and their substance is now given for the weekly periods in turn.

14. iii. Sowing.

26. iii. and 27. iii. Most of the grains forced their plumules through the soil on these days. A few were later.

13. iv. The first dry-weight samples were lifted. All the lifted plants—both of *P* and *A*—had completely exhausted the endosperms of the mother grains. Typical plants had formed three green leaves and some half of them displayed one tiller. In nearly all cases the tiller had arisen in the axil of the coleoptile. Already, differences of development were very noticeable. Plants which had a tiller showing, were better developed all round than the others. As a matter of interest the plants lifted for dry weight were laid out in what, to the eye, was their order of degree of development. Weighings showed that, although in general, the eye had proved to be accurate, there were striking exceptions. A big plant with long, broad leaves and a vigorous tiller might be well down on the dry-weight scale whereas a comparatively stunted one would be high up.

This occurred in every week when such eye-tests were made. The most reliable index of degree of development in this early stage appeared to be the length and stage of the first green leaf (*i.e.* excluding the scarious coleoptile). This leaf never attains the length or acuteness of tip which characterise the subsequent foliage leaves. It appeared that the better developed the plant, the broader was the first green (foliage) leaf and the blunter its tip (see § III below).

20. iv. Extreme inter-plant differences of development, adumbrated last week, were now apparent. Among a number of plants, all apparently thriving, were some with 4 leaves and 1 large tiller, others with 4 leaves and 2 (or even 3) much smaller tillers. Tillering it seemed, was completely at the mercy of small environmental and other predeterminative differences such as might exist between one plant and its neighbour in the row. Some idea of the general—not exceptional—incidence of fluctuations is afforded by the details of a typical row of *P* plants lifted on this day. [Damaged plants and those which germinated late, are excluded.] The successive rows of the tabular statement are:

A = Order of Merit of the Plant as shown by its dry weight.

$B =$ " " " " judged by eye.

C = Number of leaves on the main axis.

$D =$ „ tillers (excluding, of course, the main axis).

E = Dry weight of plants (mmg.).

<i>A</i>	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
<i>B</i>	1	2	4	3	9	5	6	10	12	7	11	13	14	15	8	17	16
<i>C</i>	4	4	4	4	4	4	4	3	3	4	3	3	3	3	4	3	3
<i>D</i>	2	2	2	2	2	2	2	0	1	1	0	1	1	0	1	0	1
<i>E</i>	1129	1070	938	909	892	891	856	827	792	779	778	756	690	685	684	540	481

The Table—one of many such—is eloquent of the extraordinary difficulty which lies in wait for any attempt to study quantitatively the growth and development of graminaceous plants.

An obvious warning must be uttered in regard to observations upon numbers of tillers. The record "one tiller" must, perforce, apply equally to a plant whose tiller is just sufficiently developed to be visible as to another whose tiller is (measured to the tip of its encircling first leaf), two inches long.

Plumage appeared to be doing slightly better than Archer. Between the 2-inch and the 4-inch sowings the apparent difference in vigour was exceedingly small and yet their rates of formation of tillers were distinctly different (data are given later).

27. iv. In the previous week the typical plants of *P* and *A* had 4 main-axis leaves and 1-2 tillers. This week marked an advance to 5 leaves and 2-3 tillers for *P*; for *A*, 4 leaves and 2-3 or 4 tillers. In almost every case, one of the tillers was a sub-tiller of the first main-axis tiller, which by this time, itself had 3 leaves.

The roots were carefully dug out. In all plants the primary (seminal) roots were strongly developed and could be traced readily to a depth of 10.0 cm. Secondary (adventitious) roots were also developing. Most of the plants had 2-3 or 4 of them the maximum length usually being 4-5.0 cms. Between *P* and *A* the difference, described fully in § V below, was found. As a rule the secondary roots were growing from only one node of the stem but in a few cases growth had commenced from a second node as well.

4. v. In well-advanced plants the first and second tillers from the main axis had themselves formed a first tiller. It began to be clear that, despite the precautions to secure uniform depth of sowing, the plants displayed several different modes of tillering. For example, there were plants in which the second-formed tiller of the main axis was more advanced in growth than the first formed. And again, plants having in all three tillers, might be of the type $T_0-T_1-T_2-T_3$ or $T_0-T_1-T_2-T_{1(1)}$. [T_0 = main axis, T_1 , T_2 , etc. = successive tillers of the main axis; $T_{1(1)}$ = first tiller of T_1 , etc.]

11. v. Leaves, tillers, and both kinds of root showed regular advances upon the previous week. Between *P* and *A* there was little to choose save that the root difference was again confirmed by digging and that *A* had tillered very slightly more than *P*.

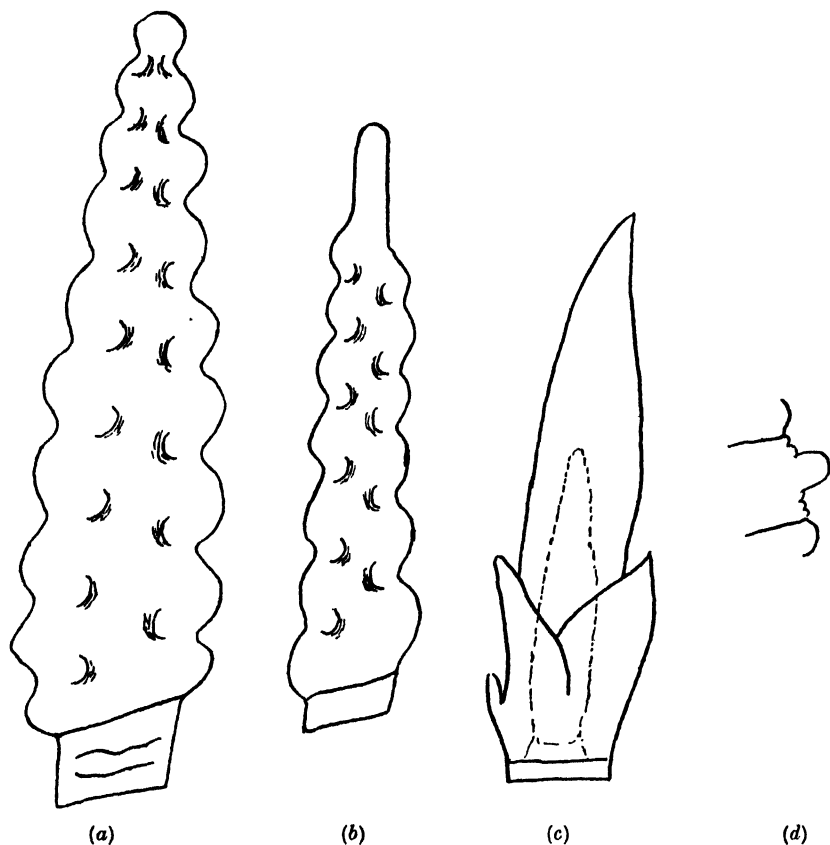
The primordia of the ear were by this time sufficiently large to permit of ready extraction and examination. Even the very small tillers had commenced to lay down their ear primordia. Fig. 1 (a)-(d) with its explanatory notes gives an idea of the various developmental stages.

In the root, *P* had maintained its superiority in adventitious growth while *A* had much the bigger range in its primaries.

18. v. There was a difference between *P* and *A* in the rate of elongation of the stem internodes, a process which had just become noticeable. Archer, elongating more rapidly, appeared somewhat "leggy" its relatively narrow leaves accentuating this. Plumage, by contrast, was a "squat" plant with broader leaves.

Development of primordia was distinctly further forward as Fig. 2 indicates. From this figure it may be seen that the later-formed tillers

had made such rapid progress in ear formation that they had almost reached the same stage as the earlier ones.



The figures are reduced from camera-lucida drawings.

Fig. 1 for 11. v. is typical of both *P* and *A* plants of average development. The main axis was usually at the stage shown by (a) and the tillers in succession at stages such as (b) or, for later tillers, (c). In a few of the more forward main axes the simple protuberances of (a) had begun to show differentiation as in (d). In all stages the young ear was completely encased in leaves but these are shown in (c) only.

25. v. There was no very noteworthy feature and, in comparison with previous weekly periods, the one ending 25. v. seemed to have brought a small change in development. In the primordia of the more forward stems (T_0 , T_1 , and T_2) an active differentiation of the formerly rather featureless "protuberances" was apparent.

The later-formed tillers seemed to have developed more rapidly than the earlier-formed and by this time had begun to vie with them in growth. This phenomenon proved to be continuous and the closeness with which the tillers of individual plants followed one another in flowering was a final demonstration of it.

Many of the damaged plants—*e.g.* leaf or main axis eaten off—had by this time produced a considerable number of new tillers; indeed in several instances they had more than the typical normal plants. Such tillers were naturally much smaller than those of normal plants.

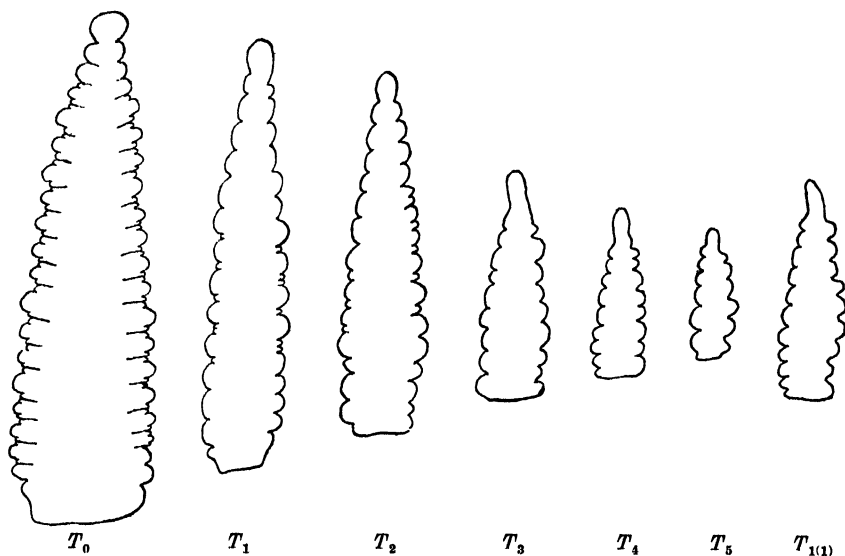


Fig. 2 for 18. v. Many plants were completely dissected and drawings made of the ears in all their stems. The series $T_0, T_1 \dots$ represents a typical plant of six tillers—in advance of the average in tillering. T_0, T_1 and T_2 are in successive stages of differentiation and in all three the process is most advanced in the “lower-quartile” part of the ear. It may be observed that $T_{1(1)}$ is about equal to T_3 and ahead of the other main-axis tillers T_4 and T_5 . The drawings are to scale and therefore give the relative life sizes.

1. vi. By this time the cumulative effects of the drought were well marked. The plants had a wilted appearance, this being particularly the case with the latest formed tillers. From a general examination of all the beds it was concluded that *P* had suffered considerably more than *A* from lack of water.

The past week had clearly been one of great development in the ear primordia. Small, finished, ears were found in the main stems of the most forward *P* plants, *A* being somewhat behind in development. Such

ears were some 3.5 cm. long in the rachis with awns protruding a further 3.0 cm. Anthers, in the median florets of such ears, were clearly visible but the paleae were relatively short. Later tillers showed varying degrees of advancement between the completely differentiated ear and the stages already described for previous weeks. While it would be exceedingly difficult to decide upon the "average" stage of ear development (of T_0) for the week, it is quite safe to describe the period 25. v.-1. vi. as one of very marked activity in ear formation.

8. vi. The ears of the main axes were fully formed. Though normal in length they were very slim for the paleae had not commenced to dry and stiffen. The florets appeared complete, the paleae now completely encasing the anthers.

Shortage of water had wrought a certain amount of damage among the latest-formed tillers which were still very small. Many of these were dead and an approximate count showed that *P* had both the bigger proportion of such tillers and the bigger percentage of loss among them.

15. vi. In both *P* and *A*, the tip of the awns of the more forward plants began to emerge from the sheath of the top leaf on 10. vi. By 15. vi. the amount of emergence was up to 2 inches. It follows from this (see § VIII below) that in some ears fertilization was about to take place.

Between *P* and *A*, the differential mortality among small, late, tillers, was again observed.

During the past three weeks a progressive dying down of the lower leaves of all the plants had been observed. It was estimated that on 15. vi. about one-third of the total leaf area was completely devoid of chlorophyll.

22. vi. It was found that fertilization, followed by the usual rapid development of the seed had been general in both *P* and *A*. The ovaries were about 0.75-1.0 cm. in length on the main axes of typical plants.

Leaf tissue had continued to lose chlorophyll and die and probably a half of the leaf area was, in most plants, thus affected.

29. vi. Apart from the steady progress of ripening there was nothing of interest to record.

6. vii. In almost every plant the top leaf alone retained any chlorophyll and even this, at the tip, had begun to turn yellow.

13. vii. Only in exceptional plants was any chlorophyll tissue to be seen in the leaves. The colour was the "yellow" or "golden" one which characterises the first stages of ripening. In the leaves and stems there was still a good deal of water.

20. vii. The ears borne by the main axes were, in many cases, ripe.

Those of the tillers were successively behindhand and, e.g. *T*₄ had, in some cases, traces of chlorophyll in the paleae.

27. vii. Harvesting was carried out, for the main axis ears were in danger of shedding their grain if left any longer and the principal tillers had completely ripened their ears.

§ IV. THE COLEOPTILE AND THE FIRST GREEN FOLIAGE LEAF.

The coleoptile is the membranous sheath of the plumule and is characteristic of the gramineae. Percival (5, p. 44) opines that it is a leaf sheath to which no lamina is attached. It was regularly observed that, under a number of different conditions of growth, *P* had a longer coleoptile on the average than had *A*. Water cultures made in the spring of 1919 afforded an opportunity to test this matter carefully. The seed used for the cultures was of the "modal" weight of a large carefully picked bulk in the case of each variety. Measurements of the coleoptile were made as soon as it was of sufficient length to allow this to be done. With striking regularity the coleoptile of both *P* and *A* plants reached or just exceeded a length of 0.5 cm. on the eighth day after the grains were set to germinate. From four to five days later the maximum length was attained. For *P* this was 2.3–2.4 cm., for *A* 1.4 cm. This simple, readily measurable difference is one of the most constant of the few which have been observed. In itself it is trivial but as one of a group applicable to the difficult problem of distinguishing the races of the cereals, it has a distinct importance. Like some other features—hypocotyl length, mode of tillering, etc.—it is influenced by depth of sowing and it has become clear that water cultures offer the best opportunity for its critical employment.

As is well known, the first green (foliage) leaf of the gramineae is shorter and blunter than all the subsequent ones. Measurements of its mean length for *P* and *A* have been made under various growth conditions and it appears that this is always slightly greater for *P* than for *A*. Like the coleoptile it is somewhat strikingly constant in length.

The plants lifted weekly in 1921 for dry-weight determinations were measured for length of lamina of first green leaf. The mean lengths (cm.) were:

<i>Date</i>	<i>P</i>	<i>A</i>
13. iv.	9.50	8.10
20. iv.	9.06	8.57
27. iv.	9.40	8.40
4. v.	8.29	7.59

No weekly sample contained more than 20 plants of each variety so that, for the first three dates, the mean length for each variety may be regarded as fairly constant. It will be seen that on 13. iv.—a month

after sowing and seventeen days after the average plant had pushed its plumule into the air—the lamina had attained its full length for *P*. For *A* the maximum was a week later. Continuous decrease in length—well marked at the 4. v. measurement—follows the attainment of the maximum. This phenomenon has been observed in water cultures in which daily measurements were made on the same plants, but the decrease was less marked than that exhibited by the above weekly averages of separate samples of plants. Decrease soon ceases, of course, and is possibly simply a result of drying.

The actual means of the water-culture measurements were $P = 11.9$ cm. maximum length and $A = 10.6$ cm. Thus the first green leaf (lamina) like the coleoptile is an index of the difference in race between *P* and *A*. An index of inter-race difference is valuable according to its own constancy from plant to plant and the magnitude of its difference as between races. Regarded in this way it appears that, even in the early stages of growth, first-leaf length is a far better index of “variety” than is dry weight—a conclusion which applies, of course, only to the case of Plumage and Archer barleys.

Harlan⁽¹¹⁾ appears to be the only plant breeder who has interested himself in early growth characteristics. He has found very emphatic differences and, if he has done no more, he has certainly established a new and valuable form of diagnosis for plant breeding and genetic work.

There appears to be scope for further study of the diagnostic value of juvenile characters in barley.

§ V. THE ROOT SYSTEM.

In all plants, the root system has received far less attention than the aerial parts. This is particularly the case in the Gramineae whose characteristic system makes investigation extremely difficult. Like all monocotyledons they form adventitious roots early in life, but the functions and relative importance of these as compared with the seminal roots, have never been made clear. It has not infrequently been stated that the seminal roots function in early development and then die, their duties having been assumed by the adventitious system. This is erroneous. In hot climates wheat and barley plants are often found to possess an extensive living seminal system even at harvest time: and in some such cases the development of adventitious roots appears to have been completely suppressed. Even in England the seminal system may sometimes be observed to persist almost until the plant reaches maturity, its size and condition suggesting that it has had a very important share in the

activities of the plant. The influence of the seminal system during juvenility is beyond question so that it can hardly fail to have a very considerable "pre-determining" effect upon the final form of the plant. The investigations of Dr Winifred Brenchley and Miss Violet Jackson (43, 44) have afforded an excellent account of the anatomy of the two kinds of root. The differences of structure which they have demonstrated are strongly suggestive of corresponding functional differences.

Attempts have been made to test the relative importance of the seminal and adventitious systems in the following manner. A small four-legged stool was placed upon soil contained in a flower pot. In a small hole in the top of the stool a barley grain was placed like an egg in a very small egg cup, the base of the grain protruding downwards through the hole. The grain was kept covered with wet cotton-wool until it germinated. The seminal roots grew rapidly downwards and entered the soil and the plant began to develop quite normally. For some 3-5 weeks no adventitious roots arose but they were freely formed a little later on and with them, a few tillers. In a few cases, plants produced one or two tillers without forming any adventitious roots but this was rare. As a rule, plants which formed no adventitious roots, failed to tiller and appeared to be generally backward in growth. Whether this retardation resulted directly from the failure to form secondary roots or was simply concomitantly with it, a sign of physiological poverty, it was impossible to decide. It is clear that adventitious roots can arise at a height of up to two inches above the surface of the soil and grow down into it but at present "stools" of greater height have not been tried. Attention will naturally have to be directed to the relation between adventitious root development and the humidity of the atmosphere. As is well known, in barley plants in the field those adventitious roots which become sufficiently developed to function, arise, like most of the tillers, just below the surface of the soil.

Efforts were made to obtain comparative observations upon the root systems of *P* and *A*. Some investigators have weighed the root systems of plants, *e.g.* King⁽⁸⁾ and Beaven⁽⁴⁰⁾ and have determined the value of root : rest of plant. Root weighings were conducted upon some plants (about 200 each of *P* and *A*) grown in flower-pots in 1920. By carefully washing the "ball" of earth from the pot, clean extractions seemed to be possible, but under the microscope numerous silica particles were seen to be adhering to the finer root branches. It proved impossible completely to remove these either mechanically or by washing with water, dilute KOH, or dilute HCl. Considerable errors in weighing were to be

expected but 200 plants of *P* were finally re-cleaned, dried, and weighed. The ratio—weight of root to weight of rest of plant—was exceedingly fluctuable. The plants themselves were far from uniform but ratios such as weight of grain to weight of straw, etc., exhibited a much closer approach to constancy than did any ratio involving weight of root. It was concluded that whatever significance may lie in the weight of root of a cereal plant, that weight cannot be determined for soil-grown plants, with practicable accuracy. The success which attended King's investigations on clover, etc., was absent from the results upon barley which Beaven (40) has recorded.

Plants of both varieties were grown in soil under various conditions and careful digging was practised on the lines employed by such investigators as Rotmistrov (6), Hays and Boss (7), Weaver (9), and Howard (10). Spraying, used with such success by Howard, was also employed. Finally, water cultures were used. Under the varying conditions, each variety showed markedly different developments but investigations made in three successive years all indicated one general difference between *P* and *A*. In *A*, the seminal system is from the outset, more abundant and extensive than that of *P*. On the other hand *P* more speedily elongates its adventitious roots. This difference appears to persist certainly for three months but after that time root extraction is so difficult that the comparison cannot with safety be prosecuted further. The photographs, Plate IV—two typical water-culture plants—illustrate the difference. They are given merely as illustrations, of course, but they are fair illustrations. It was in water-culture plants that the difference was most apparent but it was clearly discernible in the plants grown under all the other conditions.

The root investigations, although extensive, failed to disclose any other certain inter-varietal difference.

§ VI. THE NUMBER OF GRAINS ON THE EAR AND THE WEIGHTS OF THE INDIVIDUAL GRAINS.

In Appendix II is a brief survey of the more important results which relate to the possible connection between "yield," in its various aspects, and ear characters in cereals. While it cannot be claimed that these have materially amplified the analytical conception of yield, they are sufficiently suggestive to encourage further study of the ear in yield investigations.

The average weight of a single ear is clearly one of the algebraic components of yield per acre and thus, in furthering analysis, must

itself be resolved into components. Algebraically there are two, viz. the number of grains per ear and the average weight of the single grain. An interdependence of these two components is to be expected and its elucidation is one of the problems involved in the analysis of yield. The average weight of the single grain for an ear, though a useful quantity, does not represent the limit to which it is desirable to prosecute enquiry upon the characters of the ear. Two ears for which this quantity has the same value and which, in addition, have the same number of grains, may differ markedly in regard to the distribution of total ear weight among the individual grains. In the one the grains may be all of more or less the same weight while in the other the range of weights may be considerable. As between different pure lines the form of the distribution may be of diagnostic importance and it may reflect aspects of the commercial value. For example, a pure line which characteristically produced in its ear a relatively high proportion of very small grains would have manifest disadvantages. These considerations suggest the desirability of studying the distribution of weight among the single grains of the ear and, indeed, in essaying a theoretical analysis of yield, it is impossible to evade this problem. From the study certain indirect advantages might accrue. For instance, in experimental work upon barley, much trouble often results from the loss of one or more grains from the ear. If it could be shown that the distribution of weight among the grains was comparatively constant and characteristic within the pure line, the weights of one or two lost grains might be estimated with fair accuracy. In the same way fluctuations in ear weight induced by the failure of one or more florets to self fertilize might, if such failure is rare and not characteristic, be lessened by a suitable correction. Biologically, it is of interest to know whether the weight of the ear can be represented with fair accuracy as a function of, *e.g.* the number of grains and the weight of some specified grain. Speculation upon this subject may range far but it is useless without experimental knowledge. Knowledge of the required kind does not exist and its acquisition must be extremely laborious. A general survey to ascertain the state of affairs, the kind and degree of fluctuation to be expected and the practicability of such a variable as single-grain weight seems the safest approach. This consideration dictated the lines of the investigation about to be described.

The pure lines—*P* and *A*—from the 1919 crop were the material investigated. A random sample of 100 well-matured, undamaged, ears was drawn for each pure line. No regard was paid to the order of the tillers upon which these ears were borne so that the samples included main-

axis ears, first side-tiller ears, etc. Every grain of every ear was weighed and in all, over 5000 weighings were made. The individual grains were weighed on a torsion balance constructed for the purpose and throughout this paragraph the unit of weight is one division of the scale of the balance. A simple convention served for the numbering of the grains. The ear was placed on the bench, tip away from and base towards the observer, with the topmost grain to the observer's right. Starting from this grain and proceeding to the base, the grains were numbered R. 1, R. 2 ... and correspondingly on the other side L. 1, L. 2 ...

There are always two difficulties in weighing barley grains—the contained water and the adherent paleae. Both grain and straw are well known to be very hygroscopic [*e.g.* Berry (22)] but drying is so difficult and uncertain [*cf.* Miss W. E. Brenchley (23)¹] that it was not attempted. Weighings were made after a three months' storage in which all the ears were under the same conditions. Check-weighings of sub-samples at two day intervals were made and readings of the wet and dry bulb thermometer were taken at the time of weighing. It was clear that, as stored, the grains exhibited changes in water content which were small in relation to the fluctuations in humidity of the atmosphere of the laboratory. The changes were, moreover, sufficiently small to introduce no serious error in the general form of the results which are set out below. In Appendix IV are given the results of determinations of the water contents of individual grains as well as of the weight of the paleae and awns. For the grain weighings about to be given, the awn was carefully cut off at the level of the tip of the inner palea.

The weighings, together with computations based upon them, make a large bulk of data but no more of this can be given here than seems absolutely essential.

(a) *Number of Grains per Ear.*

The distribution of number of grains per ear for the *P* and *A* samples of 100 ears is given in Table XIV, the average values being *P* = 26.27 and *A* = 25.51. These values naturally have a very limited significance and in illustration of this the results obtained from the 1921 crop may be noticed. They were, for mean number of grains per ear:

			<i>P</i>	<i>A</i>
Winter sown	...	...	29.63 ± 0.38	30.51 ± 0.34
Spring sown	...	...	29.24 ± 0.41	27.84 ± 0.38

¹ "It is impossible to obtain quite concordant results in drying material like grain which will continue to lose water in the drying oven at 100° C. for an indefinite period." [This difficulty has been repeatedly experienced in drying both mature and green plants. Not only loss of water and reabsorption, it is presumed, but chemical change as well, *e.g.* of the oil in the grain—are the causes.]

Here, as for the 1920 crop (spring sown) *P* has a greater mean value than *A* for the spring sowing. For the winter sowing the order is reversed. It is clear that the *P-A* difference is less than the inter-sowing difference which *A* displays so that as an inter-varietal diagnostic character number of grains per ear is likely to prove of small value. Fluctuation could have been reduced by taking ears from plants all of which had the same number of tillers. This procedure is not relevant to the present paragraph but is considered in § IX (below).

(β) *Fluctuations in Grain weight upon the Individual Ear.*

In Table XIV the 100-ear samples of *P* and *A* are classified on the basis of the number of grains per ear. It will be observed that the class R. = 13, L. = 13 is the "modal" class for both pure lines, and for the present, consideration may be limited to the ears of that class. The complete data make it clear that within the modal class of each line the ears display considerable differences in regard to the distribution of total weight among the individual grains. As an illustration the full data for two modal-class ears of *P* are given in Table XVI. These ears have been selected at random and are typical. From the convention for numbering the grains—explained above—it follows that the order of the grains along the rachis, from tip to base, is R. 1, L. 1, R. 2, L. 2, etc. Both the ears in the Table show a rise in weight from R. 1 to L. 9 and a fall from L. 9 to L. 13. Rise and fall are not continuous but are disturbed by grains such as L. 5 or L. 6 on the first ear whose weights deviate from the general "pattern" of the relationship between weight and position. The grains of the separate sides of the ear display similar patterns with similar disturbances.

Every ear of every class is characterised by a weight-position relationship having a general resemblance to the form described above. That this is so might be learned from eye inspection and the importance of the "pattern" must depend upon its constancy for individual ears. Actual measurement of this constancy would involve cumbersome calculations but a simpler method adequately illustrates the state of affairs. In Table XV are given, for the modal (13-13) class of each pure line, the greatest and least grain weights, their difference, and the mean grain weight, for every position on the ear. The sequence of mean weights for separate positions on the ear may be regarded as the "average ear" of the class. For both *P* and *A* the average ear displays a fairly uniform sequence of values attaining its maximum at L. 10. When, however, the sequences of

the individual ears are considered, it becomes apparent that in almost all cases there are marked irregularities. [For economy of space the full single-ear data are not published.] In the two ears used for illustration in Table XVI the sequence is irregular and, moreover, the maximum is at L. 9 instead of at L. 10 as in the average *P* ear. Actually, for the combined single ears of the class, the position of the maximum fluctuates between L. 7 and R. 11 and irregularities of sequence considerably greater than those shown by the ears of Table XVI are not uncommon. Finally, the greatest and least values for every position ["Limits of weight" in Table XV] make it clear that very large differences are exhibited by the ears of a class in regard to the weight of the grain which occupies any specified position on the ear. All these facts, set forth in the case of the 13.13 ear class, apply essentially to the other classes.

It must be concluded, then, that although the weight-position relationship has a roughly characteristic pattern for all ears it is by no means constant. Neither as a diagnostic (varietal) character nor as an aid to yield-analysis does it hold any promise. And when the labour of single-grain weighings is taken into account there is full reason for concluding that the total weight, the number of grains, and their ratio are, for yield-analysis, the only practicable experimental ear attributes. These attributes are dealt with very fully in § IX below. One aspect of yielding power is reflected in the "pattern" of the "average" ear [see Section (γ) which follows] but the form of the average ear for any ear class may be found, of course, without the weighing of single grains.

The weight-position relationship of the grains of an ear—a more or less definite pattern—is of some biological interest. In the primordial ear [cf. Figs. 1 and 2] the florets develop in a sequence which suggestively resembles the pattern of the weight-position relationship at maturity. Correspondingly, time of dehiscence of the anthers and presumably therefore, fertilization as well, is characterized by a similar kind of sequence. This appears to be an instance of the "predetermination of fluctuating characters," the phenomenon first so named by Balls⁽⁴⁵⁾ and so well illustrated by his investigations.

Of greater interest but also of greater complexity, are the considerable unconformities or irregularities in the pattern of the grain-position relationship displayed by many individual ears. The examination of great numbers of primordial ears has failed to reveal irregularities in early floret development to which the unconformities of mature ears might reasonably be attributed. Anther dehiscence, however, is very frequently irregular. One or more florets undergo the process much

before or after the "sequence time." Deviations from sequence here might be correlated with those in the weight-position relationship at maturity but this seems rather improbable. For another dehiscence is, finally, no more than a mechanical rupture and in the cereals it is retarded or accelerated by very small atmospheric changes.

If the final unconformities are not to any extent attributable to early pre-determination, their cause must be sought in the filling of the grain, that complex of processes between fertilization and maturity. Harlan's exhaustive investigations⁽³⁹⁾ have cast much new light upon the period of development. One feature of his results is of present interest. At all stages of the period—and particularly the early ones—the sequence of the grain-position relationship is strikingly regular, *i.e.* free from local discontinuities. Between the circumstances of his investigation and of that here recorded, the most striking differences are the climate and the length of the fertilization-to-maturity period. As against a singularly even climate and a period of twenty-five days are the irregularities of the 1919 English summer and the period of forty to forty-five days for *P* and *A* barleys in this country. A spell of drought or extreme sunlessness is well known to inhibit grain filling in general and it may well be that a brief climatic fluctuation which but little disturbs the development of most of the grains on an ear, seriously handicaps that of one or two grains which are in a slightly different phase. In this way a small pre-determinative difference between two florets might induce a considerable maturity difference through the chance synchronization of a weather-change and a sensitive developmental phase.

(γ) *The Form of the Average Ear.*

The average weights of the grains in turn (R. 1, L. 1, R. 2...) derived from the individual values of all the ears of a class, constitute what has been called the "average ear" of that class. Only for classes 12·12, 12·13, and 13·13 are the frequencies great enough to give reasonable reliability to the values of the "average ear."

As would be expected, the total and average weights of the grains for the separate sides of the ear are practically identical for symmetrical classes (ears having the same number of grains on each side). For asymmetrical classes the two sides differ by about the weight of the last grain on the larger side. These relationships hold for the "average ears" with considerable accuracy but are only exceptionally true in the case of individual ears.

A comparison of the average ears of corresponding grain-number

classes of *P* and *A* is of interest. It may be made in a simple way by means of Table XVII which gives, in the form *P* minus *A*, the differences between the values of the *P* and *A* average ears for the grains in succession. In the 12·12 class the *P* grain is decidedly heavier than the *A* for all positions save L. 10. The 12·13 class shows four cases in which *P* is less than *A* while in the 13·13 class there are nine such cases and they form a fairly compact group in the lower half of the ear. It appears that the values of *A*, in the lower-middle part of the ear, tend to approach and even to exceed those of *P* as the number of grains per ear increases. But in the basal and apical parts of the ear the values of *P*, in all classes, exceed those of *A*. This is quite definitely the case even in the 13·13 class in which the grains of the lower-middle ear are almost uniformly the greater for *A*. The average ears of the remaining classes—excluded from Table XVII because of the low frequencies of the classes—display the same *P*-*A* difference.

It seems fairly safe, then, to conclude that *P* characteristically has relatively larger grains at the base and tip of the ear than has *A*. General observation supports this conclusion and further suggests that the inter-varietal difference is accentuated in poor and ill-matured ears. The data discussed above was derived from well-matured ears but every field crop has a considerable proportion of impoverished ears and this fact adds to the significance of the *P*-*A* difference.

The successive tillers of a plant are well known to produce successively smaller ears. [See §§ IX and XI for relevant data.] It follows from this and from the diminution in weight of basal and apical grains, that one limit to the optimum extent of tillering is imposed by the size of these grains on the smallest (latest formed) ear of the plant. Grains below a certain size are practically useless for all purposes. From what has been concluded as to the *P*-*A* difference it appears that the optimum extent of tillering is likely to be lower in *A* than in *P*. The fact bears very directly upon the "field behaviour" of the two varieties. In every field gaps are bound to be produced by the death of some of the plants and the extent to which the consequent loss of yield is compensated depends upon the response made by the survivors in the gappy areas to the increased spacings which they enjoy. Since *A* appears to produce a greater proportion of very small grains than *P* and thus to have a lower optimum tillering power, it is likely to have the smaller power of compensating for "gaps." This deduction must be regarded as tentative but it is very strongly supported by the evidence of § XI which is based upon the total yield of grain of the single plant.

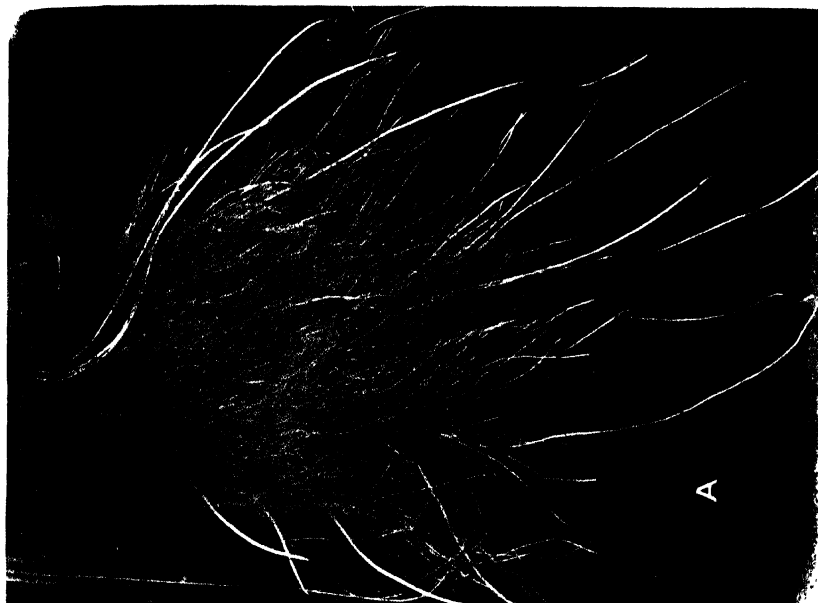
The proportions of grains of different weights is naturally an economically important attribute of any bulk of grain. Sieving would suffice for its approximate determination but for its real nature and significance to be discovered the form of the "average ear" must be determined. It is suggested that the "average ear" is one of the attributes upon which the selection of small populations, *e.g.* F_3 's or F_4 's should be based. As a fact, in selection by eye-judgment which has up to now been the customary practice, this attribute has, wittingly or unwittingly, been generally employed¹.

(δ) *Ear Weight* (*i.e.* the total weight of grains on the ear).

Among the ears of a class, all having the same number of grains per ear, corresponding grains (*e.g.* grain R. 3 on every ear) have widely divergent weights. The extent of divergence may be gauged by comparing the "Limits of weight" and "Mean weight" columns of Table XV. Comparison suggests that for individual ears in pairs there is no close relationship between number of grains and ear weight. As a test of this the individual ears of the *A* (13·13) class are represented in Table XVIII as percentages of the smallest. The wide dispersion—nearly 50 per cent. of the weight of the smallest ear—fairly represents what prevails in all the ear classes. For work on the single-ear basis, then, number of grains is not, with practicable accuracy, an index of ear weight.

In relation to the "average ears" of different classes, however, number of grains has a significance. This may be appreciated from Table XIX in which number of grains per ear and ear weight are seen to have the same order of magnitude. Average grain weight too, follows the same order with the exception of class *P* (12·13) which is slightly unconformable. The ear classes above and below the three selected ones conform to the sequence in number of grains and ear weight but show one deviation in average grain weight. That the three variables rise and fall in general harmony may be regarded as an indication that they severally reflect extent of development of the ear as a whole.

¹ In a rather novel form, the pattern of the average ear has had to be carefully considered in one class of barleys. Mixed stocks of Archer barley and various progenies of its crosses, have been selected for "short neck." This term implies that the sheath of the topmost leaf rises high on to the upper part of the top internode or "neck." Short-neck barleys suffer far less than others in the high winds which sometimes break off great numbers of ears just before harvest. Forms have been selected in which the neck was so short that the base of the ear never emerged from the leaf sheath. Two to six spikelets, thus enclosed, failed to fertilize, or set extremely poor grains. Such forms have on this account been discarded.



The concomitant rise of average grain weight with number of grains is important. It implies, for example, that an ear of 24 grains is certain to weigh more than two ears each of 12 grains. That is to say, from the point of view of yielding power, one large tiller may be of greater value than two smaller ones although simply equivalent to them in number of grains. Consequently, as between varieties, tillering power cannot be accepted unreservedly as an index of yielding power.

In assessing the conclusions of this paragraph, many of them negative, it is essential to bear in mind the nature of the experimental samples of 100 ears. All the ears were sound and well matured but they came from tillers of different orders, *e.g.* one might be from the main axis of a small plant, another from the second side tiller (third axis) of a large plant and so on. It was desirable to deal with such diversified samples in order to probe the limit of possible relationship. The facts set forth above make it clear that ear weight, number of grains, average grain weight, and individual grain weights have no analytical value for random samples of ears. But they suggest that these variables are very pertinent to inter-varietal comparisons in which plants of the two varieties are compared tiller by tiller.

The counting and weighing of single grains is exceedingly laborious and the results of § XI (below) on the significance of the number of grains borne by the whole plant afford hope that analysis can be extended on this less detailed basis.

(To be continued.)

APPENDIX I. The Effects of Upside-Down Sowing of Barley Grains.

Kulkarni (2, 3) found that for the seeds he tested there was a definite difference between his upside-down or "base up" and his right-way-up or "base down" sowings. The difference was first shown in the form of delayed germination and subsequently in after growth to such an extent that he was led to predict a lowering of the yield. Fluctuation so seriously affects quantitative work upon the cereals that a test was made of this suggested cause. It took the following form for each of the varieties (*P* and *A*). From twelve good ears, the best six grains were taken from one side, together with their neighbours from the other side of the rachis. These were sown in holes of uniform depth dibbed in boxes containing three inches of sand. The two sets, each of six grains, from every ear, were sown in neighbouring rows the one being sown "base up" and the other "base down." Thus "ups" and "downs" occupied alternate rows throughout the seed boxes. Since half the grains from every ear were

"base up" and the other half (their opposite members on the ear) were "base down," the errors due to "sampling" were made as small as possible. There were, for each variety, twelve sets (each of six grains) sown "base up" and twelve sown "base down."

The test, as here described, was duplicated by adopting two depths of sowing (half-inch and one-inch). Counts of germination were made daily at 9.0 a.m. and 6.0 p.m. For each variety at each depth of sowing, there were 72 pairs of grains (a "base up" and a corresponding "base down" grain making a pair). The method of selecting the grains made the members of every pair strictly comparable so the results were worked out on the "pair" basis. The complete tables of observations are lengthy and as they have no special interest a summary of them is given. It shows the mean periods of germination for the different categories of pair, the numbers of pairs, and (in italics) the differences of the mean periods.

Results of pairs	Variety and depth			
	<i>P ½ in.</i>	<i>P 1 in.</i>	<i>A ½ in.</i>	<i>A 1 in.</i>
"Up" germinated before	—	2 pairs	4 pairs	3 pairs
"down"	—	9.0 and 9.5	8.75 and 9.87	8.33 and 10.00
	—	<i>- 0.5 days</i>	<i>- 1.13 days</i>	<i>- 1.67 days</i>
A grain failed to germinate	7 pairs	14 pairs	4 pairs	2 pairs
"Down" germinated before "up"	65 pairs	56 pairs	64 pairs	67 pairs
	7.71 and 9.04	8.17 and 9.50	8.06 and 9.36	8.59 and 9.74
	<i>1.33 days</i>	<i>1.33 days</i>	<i>1.30 days</i>	<i>1.15 days</i>

There was thus a delay in germination of about 1.3 days at both depths of sowing. The plants were allowed to grow until their endosperm supplies were exhausted and as far as the eye could judge, the later "base up" had, by this time, completely caught up the "base down." It seemed improbable that the delay in germination would have involved any noticeable difference in after growth or yield. Kottur⁽⁴⁾ came to the same conclusion in so far as effect on yield was concerned. The effect appears, in fact, to be very small and, of course, purely mechanical.

APPENDIX II. Some Notes on Ear-character Investigations.

In the cereals, more perhaps than in most other plant groups, diagnostic characters are predominantly those of the inflorescence or ear. Exceptions are found in winter hardiness, length of life cycle, disease resistance, tillering, and length and solidness of the straw. Most of these are difficult to assess and obscure in inheritance. Naturally, therefore, investigation has been concentrated upon ear characters whose immediate economic importance has reinforced their other claims to attention.

Ear characters had found a place in farming tradition long before they became the subject of experiment. In wheat, the "square" ear exemplified by Square Heads Master in contrast with such a wheat as Fife, has long been regarded as indicative of yielding power. The "set" of the ear has been similarly interpreted. It implies the number of grains per spikelet and, as a fact, is simply another expression for the squareness of the ear. Length of ear in two-row barleys is a popular criterion. Despite the familiar differences in "denseness" of ear which our common barley forms display, a long ear usually betokens a great number of grains per ear. But the six rows of grain on the ears of the "winter" barleys has not deceived the farmer into expectations of heavy crops. He has long been aware of the association of this characteristic with low tillering power. It is of interest that some of the latest continental winter barleys have given clear indications that this association is not inevitable. Some oat varieties illustrate the failure of agricultural opinion properly to assess ear characters. In not a few of them the main-axis panicle is very large and imposing: but—a fact not apparent in exhibition sheaves—the side-tiller panicles are almost worthless. And in like manner the "3-set" spikelet of some forms and the "4-5-set" spikelet of *Avena nuda* derivatives, have been deceptive. Grains in excess of two per spikelet are apt to be very small and to have an extremely high proportion of "husk."

Ear characters such as have been described have played an important part in the evolution of our present-day cereal forms. Their use has sometimes been misleading but on the whole it has certainly wrought improvements. For further progress more precise knowledge is required. The possibility of rigid associations between ear characters and straw characters, etc., must clearly be explored as must the relationship between the form of the ear and the yield per acre.

At first, investigation was simply a quest for simple morphological characters such as presence and absence of awns, which could be accepted as indices to yielding power. The quest was stimulated by the ease with which the Mendelian inheritance of these characters could be demonstrated. Failure attended the comprehensive investigations which were made and at the present time attention is limited to those ear characters which can reasonably be supposed to be "components of yield." With the exception of features such as a tendency to grain shedding at harvest, these "economic" ear characters are measurable with fair accuracy. They fall into four simple categories:

- (i) lengths, *e.g.* of rachis or grain;

- ✓ (ii) times of flowering and ripening or length of life-cycle;
- (iii) numbers, *e.g.* of spikelets or grains;
- (iv) weights of ears and grains.

In reviewing the results so far attained it is desirable to give a liberal interpretation to these categories. Many ear characters which have been investigated have no apparent economic significance but they lend themselves to metrical representation and their behaviour indicates the difficulties and possibilities of working with similarly metrical characters of commercial importance. Two lines of investigation should precede the final "synthesis" of high-yielding strains by hybridization. First of all the "components" of yield must be determined—the ear and other plant characters of which yield is the expression. Then the modes of inheritance of these components must be ascertained that the limitations of the final "synthesis" may be known. The evidence of genetic investigations is thus seen to come within the purview of these notes.

(i) *Length Characters.*

The genetics of glume length and grain length in wheat present features of general interest. In a *T. polonicum* × *T. durum* cross, length of glume beyond a certain limit has been shown [Backhouse (47)] to be inhibitory to the presence of hairs on the glumes. And from the same cross there is evidence [Engledow (48)] that a single factor governs both glume length and grain length. It seems possible therefore that in this cross the presence of hairs may imply a limitation of grain length (and probably of grain weight as well).

Rachis length appears from the work of Harlan (11) to have a considerable diagnostic value in barley varieties in its relation to number of spikelets. Its inheritance, investigated by Hays and Harlan (18) is of some complexity but yet not such as to defy more extensive straightforward investigation. Parker (19) found that in wheat the length of the rachis showed a remarkably high correlation with the number of spikelets. Thus within a pure line population, rachis length is an accurate index to an important component of yield per acre. It is significant that among the English wheats no high-yielding form has a really lax rachis. Moreover, a lax rachis almost invariably accompanies a long straw though American Club is a striking example of a long straw and a very dense ear. These generalizations are unlikely to hold for some of the numerous hybrid wheats which have found no place in field culture. No exact data are available but the complex nature of rachis length and

density in wheat is well established as is the fact that these characters are inseparable from some other of the attributes of the wheat plant.

Studies of the individual ears of the wheat plant [Engledow and Shelton⁽¹⁾] have reflected a feature of some general interest. Glume length, rachis length, and the ratio have different values for the separate ears of the plant and the ear-to-ear correlations of these are of the order of + 0.5 for all three of the variables. Even if observation be restricted to a specified ear of every plant (*e.g.* the main-axis ear) the average values are different for populations of 1-ear, 2-ear, etc., plants. Thus in work upon ear characters a selected constant ear-number population is requisite to ensure high probability of result.

(ii) *Time Characters.*

These have been made the subject of a separate appendix (App. V) but reference must be made here to the work of Yamaguchi⁽¹⁶⁾ on rice. He studied, for the individual florets of the panicle, time of flowering, weight of glume, and weight of caryopsis and sought the relationship of these characters with each other and with the position on the panicle. Over the whole panicle there appeared to be a rough general parallelism among the characters but the actual correlations were rather puzzling. That between flowering time and weight of caryopsis was low and negative while that between flowering time and weight of glume was high and positive. It must be remembered, that at flowering time the glume is almost fully formed while the grain is only about to form. Thus post-fertilization environment is likely to be reflected in the grain far more than in the glume and in this fact may lie the explanation of Yamaguchi's curious result. In it too, there seems to lie a warning that close relationships are not to be expected between lengths of glume, rachis, etc., and weights of grain. Relationship ought naturally to be sought between variables whose environmental conditions have been strictly comparable but unfortunately no other simple ear character is determined in exact synchrony with weight of grain.

(iii) "*Number*" Characters.

In both varietal and genetic studies few plant attributes have proved so evasive as those which take the form of pure numbers. Such characters have been but little studied in the British cereals and evidence must therefore be drawn from other plants. Balls⁽⁴⁹⁾ attempted to trace the inheritance of the number of divisions of the boll in cotton. To cope with fluctuation he devised an ingenious scale of 21 grades. The number

of divisions was inconstant on an individual plant and therefore the grades of the scale were based upon the proportions of bolls having specified numbers of divisions. This precaution was able to expose, in hybrid progenies, no more than a suggestion of the occurrence of segregation. Groth (50) studied a series of pure number characters in the tomato. Among them were number of "small segments" of the leaf, and of loculi in the fruit. Great fluctuation was found and arithmetic mean values were adopted as the "characteristic numbers" of the various strains. In general the F_2 distribution was unimodal but the numbers of plants in the separate F_2 's were usually very small (e.g. from 47 to 207) and it is difficult to decide whether size of sample or complexity of inheritance was responsible for the unimodality. Burt-Davy (51) found in maize that the number of rows of grains might be different for the upper and lower cobs of the same plant (two cobs per plant is common in South African maizes). Although the number of rows per cob was greatly influenced by the environment, there were indications of a heritable tendency towards a characteristic number. The F_1 of an 8×18 cross contained plants having from 8–16 rows but the distribution for the complete F_1 was fairly well grouped around 12.

These results do not encourage the hope that the pure number characters of the ear in the British cereals will prove generally amenable to accurate investigation. It seems, indeed, that pure numbers should be regarded as very obscure expressions of the true "units" of heredity. Nevertheless in examining large populations of various cereal forms it is impossible to escape the impression that in some instances there are quite characteristic pure-number differences. Thus the "set" (number of grains per spikelet) in many Chinese forms of *Triticum vulgare* is always greater than in any form of *T. durum*. And again, the number of grains per spikelet of *Avena nuda* (5–8) is markedly greater than in any other cultivated species of the genus. Such derivatives of *A. nuda* as the Sir Douglas Haig Oat constantly display, at any rate in the upper spikelets of the panicle, a greater number of grains than is found in *A. sativa* or *A. orientalis*.

From these two bodies of evidence, the one derived from experiment, the other from general observation, it is concluded that investigations on pure numbers must have a limited application in the British cereals. Well-marked differences such as have been described in *Triticum* and *Avena* may be of importance. Their relation to other plant characters and their mode of inheritance seem likely to prove practicable objects of investigation and possibly, also, matters of economic importance.

Small numerical differences, however, will not repay the labour of investigation.

(iv) *Weight Characters.*

The published data relating to weight characteristics of the ear in cereals is very extensive. In most cases, however, plant characteristics, and not ear characteristics are concerned. Experiments on maize have been made in great number and Richey (52) has published an admirable review in which he makes clear the value of "ear weight" as an index to selection. Cunningham (15) found, in maize, a relationship between "length of kernel" and "yield."

In wheat, interesting studies have been made by Hume, Champlin, and Fowles (13) and by Arny and Garber (14). The first mentioned authors found a very low correlation between the length of the maternal ear and the yield of grain produced by the offspring plants, twenty such plants being raised from every maternal ear. Yield per plant is a very fluctuable character and, perhaps, a sample of twenty plants is to be regarded as inadequate particularly in an investigation wherein the vagaries of two successive seasons were operative. The work of Arny and Garber, repeated in four successive years, although it relates entirely to the characters of the complete plant, is a noteworthy voucher for the amenability to investigation of weight characters in wheat.

Kiessling (20), in an investigation upon barley, has contributed to the very slender bulk of inheritance data upon the weight characters of the cereals. His chief concern was the percentage nitrogen content of the grain but he was led to conclude that average grain weight was a varietal and heritable character.

Little direct evidence is available concerning the weight characteristics of the ear (as distinct from the plant). But the results which have been considered encourage the hope that such characters will, in suitably conducted investigations, prove to be practicable experimental variables. Their importance in yield studies is at once apparent when efforts are directed towards the preliminary analysis of yield per acre, *i.e.* the algebraic analysis.

APPENDIX IV. Weight of Awn, Water Content, Weight of Paleae, and Nitrogen Content of the Individual Grain.

In § II of the text is recorded an investigation into the weights of the individual grains of the ear. Since the grains were air dried it remained a possibility that the inter-grain weight differences were in some measure attributable to differences of water content. This made it desirable to test the fluctuation of water content among the grains of the ear. Water content is one of a series of grain characteristics which, though possibly negligible in samples of say 2000 plants, would certainly have to receive consideration in working on the single plant basis. Other characteristics of this kind are the amount of loss in dry weight by "washing out" through rain or dew, and the weight of the adherent paleae. Strictly speaking the paleae ought to be excluded in assessing "yield." From a number of investigations it is clear that the awn is an important organ of transpiration and this suggests that the weight of the awn may be related to the weight of endosperm. Again, analyses, made originally by Johannsen, have established a relationship between weight of grain and percentage of nitrogen. In bulk, the large grains from the middle of the ear were shown to be less nitrogenous than the small grains at the tip. Individual grains were not analysed.

No attempt has been made to test the losses in dry matter for which "washing out" is responsible. Judging from the results of Le Clerc and Breazeale these may amount in the oat, to the following percentages of the total amounts absorbed: for N 2 per cent., for P 33 per cent., for K 36 per cent. Berry⁽²²⁾ comparing these values with those which his own investigations furnished agrees that cut material may be severely "washed out" by rain but opines that while the plant still lives losses are likely to be small.

The foregoing considerations suggested that the difficulties and the possibilities of single-plant investigation could be better appreciated by the accumulation of knowledge concerning the following attributes of the individual grains of the ear—(α) the weight of the awn, (β) water content, (γ) the weight of the paleae, (δ) nitrogen content. To ascertain statistically reliable values would have been an impracticably extensive undertaking. Only a preliminary survey was attempted and its results are given below.

(a) The Weight of the Awn.

Both the actual weight of the awn and the proportion it bore to the weight of the grain, were found to fluctuate considerably among the single grains of an ear. In general, the grains of the upper part of the ear and the last two or three at the base, had proportionately lighter awns than the remainder. An approximate "sequence" was displayed by the proportionality in the successive grains, which resembled that of the actual weights of the grains (*vide* § VI of the text) in form and in the occurrence of local discontinuities. The resemblance harmonizes with the speculative possibility that, the awn being largely responsible for transpiration, its size should be reflected in the amount of reserve material translocated to the grain to which it belongs. It is noteworthy that in the nominally "awnless" barleys, so many of which at times produce short "scurs," the length of the "scurs" of the successive grains show a sequence exactly similar to that of the weights of the awns for normal "awned" barleys. The full data of awn weight is too extensive for publication here but a fair and typical illustration is afforded by the values for two *A* ears contained in Table XX. This illustrates the general sequence, the nature of its irregularities, and the extent of inter-grain differences in the awn-weight : grain-weight proportion. Extreme cases displayed considerably more marked irregularities.

To harvest, transport, and store barley ears without damage to the awns requires elaborate precautions. These however would be repaid, if it were possible to weigh the complete ear—awns, rachis, and grains—and to use the total weight as an index to the actual weight of grain. The possibility rests upon the constancy of the inter-relationship of the three weights—awns, rachis, and grains. This was tested by totaling the individual grain and awn weighings and further, by separate determinations of total awn and total grain weights for a series of ears. For the ear, the awns bore to the grains a weight-ratio which fluctuated between 12 and 17 per cent. Moreover, for the series of ears used—all from the same pure line—the order of magnitude of total grain weight was emphatically not the same as that of total awn weight. It appears, then, that for experimental purposes, the grain itself must be weighed and not the complete ear. Further trial would be necessary to determine the size of sample requisite to ensure the reliable calculation of grain weight from total ear weight. In inter-varietal tests, however, it would always be essential to ascertain the awn:grain-weight proportion of every variety. The "threshing" of single barley ears, including awn removal,

may be expeditiously accomplished by the use of a simple contrivance. A wire-gauze cylinder is mounted on two horizontal iron rods the one fixed the other movable along its own length. The ear is placed in the cylinder with the rods projecting into the ends, and the cylinder moved backwards and forwards four or five times. The awns, catching in the gauze are broken into short pieces. The diameter of the cylinder is adjusted to give a close but easy sliding-fit on to the rods.

(β) *Water Content.*

Miss Brenchley and Hall⁽²³⁾ have pointed out the impossibility of obtaining constant grain-weighings even after repeated drying. In this investigation it was found that after 48 hours drying changes greater than 0.2–0.4 per cent. were rare. Consequently the weight after 48 hours drying was accepted as the true dry weight provided that, after a further 24 hours drying, the total change did not exceed 0.5 per cent.

No correlation appeared to subsist between the weight of a grain and its percentage water content. Actual inter-grain differences of proportion of contained moisture were, among the grains of an ear, comparatively small. It seemed probable that neither the general form nor the unconformities of the sequence of the weight : position relationship discussed in § VI of the text, could be traced to differences of water content. Table XXI is given as a typical illustration but occasional ears displayed more marked fluctuations than are there disclosed.

Between complete ears of the same pure line and from the same plot, differences in water content were well marked. The data are not sufficiently full for the calculation of errors, etc., but they direct attention to a hitherto neglected aspect of yield trials in general. Without regard to actual dry weight, field and plot trials are commonly adduced in evidence of inter-varietal differences in yield, migration coefficient, etc. Berry⁽²²⁾ has demonstrated with striking effect how great may be the changes in water content of oat grain and straw under ordinary storage conditions. For field crops the data published by the Olympia Agricultural Company⁽³⁰⁾ deserve notice. Thus (*loc. cit.* p. 23) for four barley varieties grown in one locality the percentages of water in the grain were 23.79, 22.41, 22.14, 21.41. In another locality the same varieties had values of 15.53, 15.28, 15.50, 15.15. Again (*loc. cit.* p. 30) for four oat varieties in one locality the values were 12.90, 13.95, 14.70, 15.35. Although probable errors are not given for these determinations their general significance is undeniable. Inter-locality differences of 8 per cent. may be displayed by a variety and inter-varietal differences of 2.5 per cent. may appear

in one locality. The samples were drawn from 1-acre plots and in small chess-board, etc., plots, particularly when straw also is weighed, greater fluctuations may be anticipated.

It appears then, that in yield investigations of whatsoever scale, the accuracy sometimes claimed and always desirable, is unlikely to result until attention is directed to fluctuations in water content.

(γ) *The Weight of the Paleae.*

The adherent paleae may be removed for weighing by two simple methods. By germinating the grain and allowing the endosperm to be consumed, a clean separation of the paleae is possible but naturally the dry weight of the whole grain cannot first be determined. Alternatively the grain may be boiled in water until the paleae are loose. This was the method usually employed.

In general, among the grains of an ear, the smaller grains had the bigger proportion of paleae weight to total dry weight. An illustration of the general trend is afforded by the data for two typical *A* ears contained in Table XXII. On a small proportion of ears some of the grains were sharply exceptional to the generalization. It has been explained in § VI of the text that the relative sizes of the grains—particularly of those at the base and tip of the ear—are important in relation to yielding power. Their importance is the more emphatic in the light of the paleae-weight : total dry-weight relationships which have been shown to exist.

The extremes of the proportion of total weight represented by the paleae, are about 7–11 per cent. for individual grains. It is concluded that weight observations on single plants in yield investigations would, on this ground alone, fail to have a sufficient accuracy to permit of the separation of types as similar in yielding capacity as are those now commonly dealt with in plant-breeding practice.

(δ) *Nitrogen Content.*

Determinations of the percentage of nitrogen in single grains were attempted. The Kjeldahl method was adopted in preference to such methods as Folin's on the ground of its greater simplicity. Manifestly the accuracy of a single determination upon so small a sample must be low and the only trustworthy deductions could be those consistently displayed as a general trend. Of this kind was the fact that, in general, the small grains from the base and tip of the ear had a lower proportion of nitrogen to dry weight than the remaining larger grains. This result

is in accord with those obtained by Johnnsen and subsequent investigators who grouped apical, middle, and basal grains from a number of ears to obtain reasonably large samples for analysis.

Inter-grain differences of nitrogen content suggested that one economic aspect of tiller development was to be found in the ratio between the carbohydrate formed and the nitrogen taken up from the soil. This is further discussed in § XIII of the text.

(*ε*) *Conclusions.*

Algebraic theories of yielding power ought, if extended to their limits, to take into account the contained water and the paleae weights of the individual grains of the ear. But the investigation indicates that the fluctuations of these attributes are of an order which precludes this theoretical procedure from practice. The characters of the whole ear appear to be the ultimate ones with which investigation can at present deal. The weighing of complete ears (grains, awns, and rachis) as grain is always indefensible in small samples and in large ones it calls for preliminary tests of validity. Correspondingly, the water contained in the grain presents a difficulty and its fluctuations may invalidate yield-trial results in which it has commonly been ignored. The relation between the weights of the awn and the grain is, in connection with the transpiratory function of the awn, a suggestive one. But the irregularities displayed by individual grains indicate that grain development is only partially and conditionally dependent upon size of awn.

Table XII (which also serves as a ground-plan of the beds). The means (nos. of tillers per plant) of Tables I–XI for *P* and *A* showing the Bed number, sowing interval, and date.

Date	Bed 5=4"		Bed 6=4"		Bed 7=2"		Bed 8=2"	
	<i>P</i>	<i>A</i>	<i>P</i>	<i>A</i>	<i>P</i>	<i>A</i>	<i>P</i>	<i>A</i>
21. iv. 20	1.18 ±0.071	1.06 ±0.062	1.34 ±0.058	1.17 ±0.058	0.63 ±0.036	0.90 ±0.036	0.85 ±0.038	0.90 ±0.039
28. iv. 21	—	—	—	—	—	—	2.30 ±0.061	2.46 ±0.073
7. v. 21	4.38 ±0.173	4.82 ±0.163	—	—	—	—	3.52 ±0.085	3.53 ±0.095
25. v. 21	6.15 ±0.243	5.41 ±0.193	6.27 ±0.216	5.98 ±0.185	3.16 ±0.069	3.33 ±0.087	3.83 ±0.109	3.60 ±0.108

Table XIV. *P* and *A*. Number of grains on each side of the ear in a random sample of 100 ears.

No. of grains on	L.	10	10	11	11	12	12	13	13	14	14	15	15	16	12	14	16
	R.	10	11	11	12	12	13	13	14	14	15	15	16	16	11	13	15
	<i>P</i>	1	1	2	6	10	14	21	18	10	8	2	4	1	1	—	1
	<i>A</i>	—	1	1	14	17	19	22	6	11	6	2	—	—	—	1	—

N.B. The last three columns are unconformable. They represent three ears exceptional in having more grains on the L. than on the R. (R. and L. are determined as explained in the text.) Average number of grains per ear: *P* = 26.27; *A* = 25.51.

Table XV. *P* and *A*. For ears of the (R. = 13, L. = 13) class: showing for each position on the ear the upper and lower limits of grain weight, their difference and the mean grain weight. [No. of ears, *P* = 21; *A* = 22.]

Grain no.	Position	<i>A</i>			<i>P</i>		
		Limits of weight	Difference	Mean weight	Limits of weight	Difference	Mean weight
1	R.	33	56	23	36	58	22
	L.	41	65	24	38	65	27
2	R.	44	69	25	48	68	20
	L.	42	73	31	23	70	47
3	R.	44	79	35	48	73	25
	L.	43	75	32	52	73	21
4	R.	47	75	28	45	75	30
	L.	48	82	34	55	78	23
5	R.	53	75	22	56	79	23
	L.	52	82	30	56	79	23
6	R.	60	79	19	55	76	21
	L.	52	82	30	58	80	22
7	R.	62	85	23	51	81	30
	L.	64	84	20	55	82	27
8	R.	62	85	23	60	82	22
	L.	64	87	23	58	85	27
9	R.	56	88	32	51	86	35
	L.	64	89	25	57	90	33
10	R.	63	85	22	58	84	26
	L.	64	86	22	61	83	22
11	R.	61	87	26	61	88	27
	L.	61	82	21	59	87	28
12	R.	56	81	25	54	82	28
	L.	40	75	35	54	85	31
13	R.	40	73	33	51	79	28
	L.	22	60	38	15	70	55
Mean grain weight over the whole ear				63.61	—	—	64.78

Table XVI. Two ears of *P* chosen at random from the R. = 13, L. = 13 class to illustrate fluctuations in the weights of individual grains.

Position	No. of grain												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1st ear, R.	48.0	56.5	62.5	65.5	66.5	67.5	66.5	68.5	62.5	72.5	72.5	67.5	61.5
„ L.	55.5	61.0	65.5	66.0	70.5	61.5	65.5	72.0	75.0	69.5	73.0	64.0	54.5
2nd ear, R.	37.0	57.5	59.0	68.0	69.0	69.5	72.5	71.0	77.5	77.5	71.0	69.0	63.5
„ L.	49.0	60.0	67.0	68.5	68.0	71.0	75.0	76.0	78.0	71.0	74.0	70.0	15.0

Table XVII. The difference (in the form $P-A$) of the mean weights of the successive grains of the ear (from the top downwards) for the ear classes R. = 12, L. = 12; R. = 13, L. = 12; R. = 13, L. = 13.

Grain No.	Position	Class of ear		
		R. = 12 L. = 12	R. = 12 L. = 13	R. = 13 L. = 13
1	R.	2.1	1.7	1.6
	L.	1.5	2.2	1.9
2	R.	5.0	4.0	2.0
	L.	5.9	2.0	4.2
3	R.	6.5	3.0	1.5
	L.	4.4	1.9	0.8
4	R.	4.8	3.2	0.4
	L.	4.1	-0.4	0.2
5	R.	6.4	1.7	0.8
	L.	3.6	-0.7	0.9
6	R.	6.8	1.4	0.8
	L.	3.8	2.2	0.0
7	R.	4.0	-0.3	-0.4
	L.	2.1	2.5	-1.1
8	R.	5.9	0.5	-1.2
	L.	3.9	-0.4	-0.2
9	R.	2.6	1.5	-0.7
	L.	4.1	1.1	-0.8
10	R.	2.7	2.7	1.4
	L.	-1.5	1.2	-0.8
11	R.	3.3	0.2	0.8
	L.	3.3	4.3	-0.3
12	R.	5.6	2.3	-0.1
	L.	3.5	9.8	5.4
13	R.	—	7.7	4.8
	L.	—	—	8.5

Table XVIII. The frequency distribution of ear weight for the (13.13) ear class of A . Weights are expressed in terms of the smallest ear weight as 100.

Weight classes	100	109	111	113	114	115	117	119	120	121	122	124	125	128	129	131	133	148
Nos. of ears	1	1	1	1	2	1	1	1	2	2	1	2	1	1	1	1	1	1

Table XIX. P and A . The number of grains per ear, average grain weight and average ear weight for the classes R. L. = 12.12, 12.13, and 13.13.

No. of grains per ear	P		A	
	Average grain weight	Average ear weight	Average grain weight	Average ear weight
24 (12.12)	63.81	1531.44	59.88	1437.12
25 (12.13)	63.48	1587.00	61.24	1531.00
26 (13.13)	64.78	1684.28	63.61	1653.86

Table XX. Two ears of *A* to illustrate the relation of awn weight to grain weight for the successive grains of the ear. The weights were ordinary air-dry weights and the numbers in the Table are $(100 \times \text{weight of awn})/\text{weight of grain}$.

		Number of grain on ear													
Side		1	2	3	4	5	6	7	8	9	10	11	12	13	14
First ear	R.	10.3	11.4	13.2	12.4	13.4	12.4	14.1	15.2	13.6	14.3	14.7	13.6	14.5	10.0
	L.	9.2	10.4	13.2	13.7	13.9	13.6	14.2	13.4	13.3	12.8	14.6	14.7	14.3	11.2
Second ear	R.	12.3	13.1	16.8	15.7	15.6	18.5	18.3	18.1	19.4	21.9	25.7	20.8	20.2	—
	L.	12.1	15.9	17.2	14.0	15.5	15.5	17.1	17.5	19.4	20.4	20.3	17.6	17.7	—

Table XXI. Water content of the successive grains of an ear of *A*₂ expressed as $(100 \times \text{weight of water})/(\text{air-dry weight of grain})$.

		Number of grain on ear												
Side		1	2	3	4	5	6	7	8	9	10	11	12	13
R.		13.1	12.8	13.1	12.6	13.1	12.6	12.4	12.7	13.0	13.0	12.9	12.7	12.8
	L.	12.5	12.7	12.3	12.8	12.5	12.4	12.5	12.5	12.7	12.8	12.7	12.5	12.8

Table XXII. Weight of paleae of successive grains of the ear for two ears of *A* expressed as $(\text{dry weight of palea}) \times 100/\text{dry weight of whole grain}$.

		Number of grain on ear												
Side		1	2	3	4	5	6	7	8	9	10	11	12	13
First ear	R.	9.3	10.4	8.7	8.1	7.6	8.7	7.3	7.6	8.9	7.6	7.3	8.6	—
	L.	8.4	9.6	8.5	8.3	7.9	7.8	8.2	7.9	7.3	8.4	8.6	9.2	—
Second ear	R.	9.4	8.1	9.6	9.5	8.3	8.1	8.5	8.6	7.7	7.7	8.9	8.3	10.4
	L.	9.0	8.3	8.3	8.1	8.3	8.8	7.4	9.1	7.8	8.9	8.9	9.2	—

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THE EFFECT OF MOVEMENT OF SOIL SALTS ON STANDARDIZATION VALUES OF ELECTRODES USED IN MOISTURE DETERMINATIONS.

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(With Two Text-figures.)

IN my previous paper on the electrical determination of moisture in soils⁽¹⁾ I reserved the question of possible effects of soil salt movement in vitiating the conclusions therein reached as to the usefulness of the electrical method in practice. The present communication contains an account of some experiments carried out with a view to settling this point.

Briggs⁽²⁾ states that: "As regards the quantity of soluble salts present, it can be said that no gradual variation in the resistance due to change in the salt content seems to take place during a season." He makes an exception of the case where heavy leaching rain has fallen, when it was necessary to restandardize the electrodes.

The assumption on which the following experiments are based is that if a large portion of soil, protected from rain, is separated from all connection with surrounding parts and the water table within it maintained at a constant level; then the moisture content at any depth will vary only with the temperature and the relative humidity of the air above the soil. Consequently, if we can take a large number of observations and pick out a series made under constant conditions, except as to soil salt concentration, variations in this factor will be reflected in the resistances observed.

Apparatus. A large box $3' \times 3' \times 3'$ internal dimensions was constructed of 1" deal boards and bound with iron on the outside. In the bottom about a hundred half-inch holes were bored at equal distances apart, to allow free circulation of water through the bottom without risk of quantities of soil falling down and interrupting the connection between the soil and the water below. Four legs, one inch high and three inches square, were screwed on at the corners and sufficed to carry the weight of the box when filled and to raise the bottom slightly from the tray in which it rested. This was made of galvanized iron $3\frac{1}{2}' \times 3\frac{1}{2}' \times 3''$.

The soil used was dug from a field on the University Farm, Gravel Hill, Cambridge. It was of fairly light texture and contained a considerable quantity of stones in the lower layers. It was taken up by layers six inches thick and carted to the laboratory in bags. The lowest layer, 30"-36", was placed in the box first and tamped down tightly, then the next layer and so on up to the surface soil, so as to imitate as nearly as possible the natural condition. Each layer was watered from a can as it was packed in, but not to such an extent as to saturate it; in this way, it was hoped, the ascent of water from below would be facilitated.

The box was filled on the 20th December 1921 and the tray kept full of water until the moisture in the mass appeared to have reached equilibrium. Experiments were not commenced until 23rd January 1922.

The electrodes used were rather different from those employed in the earlier work, as it was proposed to leave them a long time in the soil and any risk of variation due to decay of the insulation had to be avoided. Carbon paraboloids an inch in length and $\frac{3}{4}$ " maximum diameter were prepared from cored arc light carbons. The bottom end was insulated as before lest some of the core substance might escape into the soil. Into the other end a straight stout copper wire was sealed with fusible alloy exactly as described in my previous paper (*loc. cit.*) except that the end was not covered with sealing wax. The copper wire was enclosed in a glass sheath of nearly the diameter of the electrode, with a cork in the upper end through which the wire passed. A hole was made to the right depth with a similar carbon and the electrode, complete with sheath, was carefully lowered into it and pressed home with the glass tube, the soil being packed in on all sides as in planting out cuttings—finally, the electrode being held in position by the wire, the glass sheath was raised about a quarter of an inch.

The final state of the electrode buried in the soil is shown in Fig. 1. In this way any possible variation due to condensation of moisture on the glass and conduction along this layer causing a virtual increase of the electrode area was avoided.

Nine electrodes of this type were made, and sunk into the soil the day after the box was filled; three in line at 3", three at 4" and three at 6" depth. Leads were soldered to the ends of the wires and carried to a mercury cup switch-board fixed to one side of the box. As no mercury thermometers of sufficiently long stem from the bulb to the 20° C. mark were available, three resistance thermometers were prepared from double silk insulated copper wire, s.w.g. 40, non-inductively wound on to wooden sticks small enough to be placed in test tubes. These were calibrated

against the mercury thermometer used on the soil surface. A correction was applied for the exposed portion of the leads as the temperature of this normally differed from that of the coil; for this purpose the exposed leads were assumed at room temperature. A change over arrangement was installed to enable direct or alternating current to be used at will.

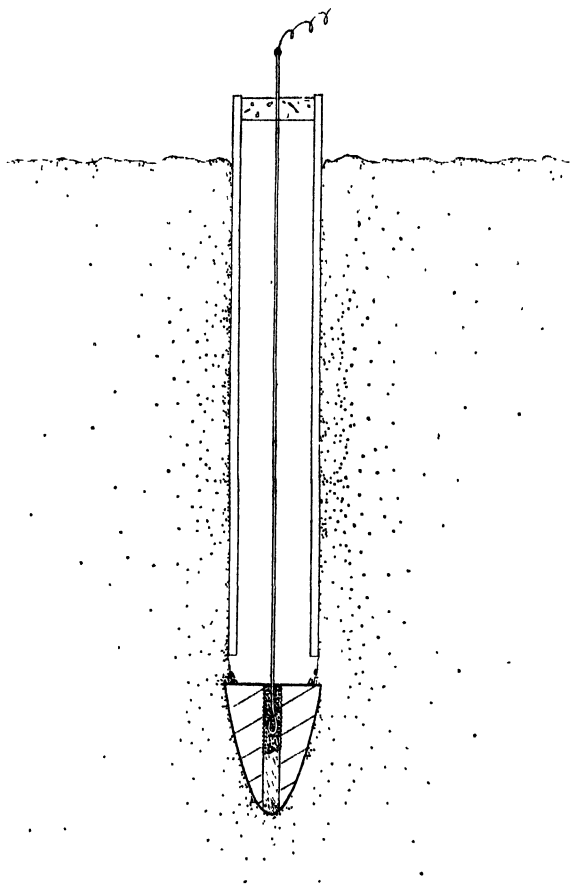


Fig. 1. Box electrode in soil.

The full connections of the apparatus are shown in Fig. 2. It is particularly important with the apparatus used that the thermometers should be in series with the standard arm of the bridge and that the resistance actually to be unplugged in this should be, say, ten times the thermometer resistance (ca. 20ω .), otherwise even when a tapping key is used some heating of the thermometer coil is likely to occur when contact is made.

When observations were being made on the thermometers the bridge current was connected through the galvanometer by the switch S_1 and the connection to the cells made momentarily by the tapping key K . The fourth significant figure was calculated from the swing of the needle. The small current which traverses the secondary in this case does not affect the experiment. For the soil resistance observations the coil switch S_2 was thrown over and the current from the secondary carried through the bridge, the switch S_1 being connected with the telephone circuit.

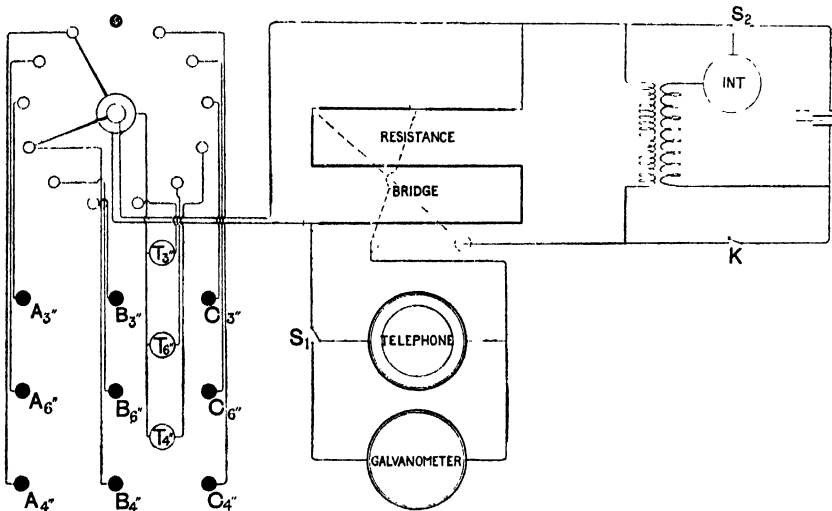


Fig. 2. Plan of connections to soil box.

The surface temperature was taken by a thermometer placed in a test tube just buried in the surface soil, while the relative humidity was determined by a wet and dry bulb hygrometer hung in the air above the edge of the box.

Errors due to variations in the mercury cup resistance, temperature lag of the insulated leads and thermoelectric effects were certainly within the limits of experimental error and have been neglected.

Results. For some little time after observations on the box were commenced there was a steady fall in the resistances observed in all cases. This is thought to have been due to the water having had insufficient time to reach equilibrium in the box. In the early spring of 1922 they became steady.

The first result to appear was that within the degree of accuracy attained and under the conditions of the experiment, the relative

humidity is without effect on the moisture content at 3" depth. Dr Keen¹ points out that this is not surprising in view of the result recorded later when 1 mm. of water was sprayed on to the soil. The figures given in Table I show this absence of effect quite clearly. They are a selection from a larger number and may be taken as quite representative—the selection was made by lot drawn by a colleague unaware of the object thereof. This being established, temperature coefficients of resistance were determined between the different pairs of electrodes so that observations could be corrected to the same temperature. My observations, which were continued until summer so as to obtain as great temperature differences as possible, gave results rather higher than those obtained by Whitney and Means (3), ranging from 29 to 39 ohms per mille per degree Centigrade change of temperature.

Table I. *Effect of Air Humidity Variation on Soil Resistance.*

Electrodes A_3, B_3 at 14°·0 C. and 3" depth		Electrodes A_4, B_4 at 13°·5 C. and 4" depth		Electrodes B_4, C_4 at 13°·4 C. and 4" depth		Electrodes A_3, B_3 at 12°·7 C. and 6" depth	
Rel. hum.	Resistance	Rel. hum.	Resistance	Rel. hum.	Resistance	Rel. hum.	Resistance
59	3370	62	2510	65	2040	59	1600
61	3400	66	2485	69	2030	65	1590
61	3390	71	2490	72	2060	65	1580
65	3405	73	2480	72	2050	67	1600
67	3390	74	2500	73	2040	69	1580
68	3395	—	—	73	2040	73	1580
71	3375	—	—	74	2030	73	1580
73	3420	—	—	—	—	—	—
73	3360	—	—	—	—	—	—

In the beginning of June the process of applying artificial rain in small amounts to the top of the soil was commenced. For this purpose a scent spray was used to put on distilled water equivalent to one millimetre of rain; this was enough to make the top thoroughly wet and further amounts were added with a fine nozzled washing bottle. To ensure even spreading in the case of the smaller amounts the top of the soil was divided into foot-squares by threads stretched across from the sides of the box and equal amounts of water sprayed on to each of these nine squares. During the spraying process the mouths of the thermometer tubes were protected by glass cones.

When only one millimetre of rain was put on it was found that it did not sink in far enough to affect the resistance of even the electrodes buried at the 3" level. Another millimetre added two days later, before the first had completely evaporated off, caused a distinct, small, fall in resistance which remained constant for more than a month and showed

¹ Private communication.

no appreciable sign of recovering itself in that time—this was on 2nd August 1922 and it must be remembered that the surface soil had been drying out under an approximation to natural conditions since the apparatus had been set up the previous December. On August 4th two millimetres of rain were applied and a short time afterwards a very marked fall was noted in the resistance between all the pairs of electrodes which gradually recovered itself in the ensuing weeks eventually, in the beginning of October, reaching a point but little below that from which it started in August. Later experiments, details of which are given in Table II, showed that whether 2, 3 or 5 millimetres of water were put on the resistance always returned to approximately the same point, the time allowed for drying being about two months in each case.

Table II. *Resistances at 16° C. between various electrodes after watering.*

Electrode pair	Equilibrium point before watering	Water added			
		1 mm. on each of two separate days	2 mm.	3 mm.	5 mm.
$A_3''-B_3''$	3025	2870	2450	2630	2615
$B_3''-C_3''$	3030	2845	2495	2725	2685
$A_3''-C_3''$	3120	2970	2525	2795	2735
$A_4''-B_4''$	2245	2025	1580	1650	1665
$B_4''-C_4''$	1765	1600	1225	1270	1295
$A_4''-C_4''$	1765	1645	1420	1390	1495
$A_6''-B_6''$	1165	1120	985	1005	—
$B_6''-C_6''$	1165	945	805	825	—
$A_6''-C_6''$	1255	1155	1040	1060	—

It will be observed that the maximum differences between the figures for each pair of electrodes in the last three columns do not exceed about 10 per cent. of the observed resistance; a change which would be caused by a variation of moisture content of less than one half of one per cent.

It was hoped to be able to get an observation after putting 10 mm. of water on. This experiment was discontinued however as the watering appeared to have very materially changed the soil texture, a hard surface crust had formed and cracked in drying and many more stones were visible in the surface than before, moreover one of the electrodes had evidently been accidentally jarred in the drying interval, which would have further depleted the number of results.

Conclusions. From various circumstances the theoretical results accruing have been disappointing for an experiment extending over some sixteen months. There is no sufficient reason for concluding that the resistances found subsequent to watering would have re-attained their original equilibria if sufficient time could have been allowed. It seems

a natural suggestion that this question may be bound up with that of the exceptional observations in the cases when 1 mm. of rain was applied on two separate days. Further there is no apparent reason for the fact that the values to which the resistances recovered after 2 mm. of water had been applied were appreciably *lower* than those to which they rose after 3 mm. had been put on—this cannot be due to any formation of air channels or the effect would have been intensified when 5 mm. were used, but it was not. Perhaps a stronger solution was depressed to the electrode level in the manner well known in leaching, but it is difficult in this case to account for the same appearing at all depths.

From the practical point of view, however, the experiments afford a sufficient confirmation of the American observations quoted at the commencement of this paper; standardization values in normal soil will apparently not be altered by every passing shower, at all events not to any material extent.

My thanks are due to Mr H. R. Davidson, B.A., of the University Farm, for his help in selecting a suitable portion of soil and in arranging for its transport to the Laboratory.

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THE APPLICATION OF THE INDIRECT METHOD OF CALORIMETRY TO RUMINANTS.

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(With Five Text-figures.)

IN the study of animal nutrition valuable information has been obtained from feeding experiments, the results of which depend upon the live-weight test. These results, however, deal only with the relative values of different foodstuffs and methods of feeding, and the accumulated data are, on the whole, not of such a nature that general physiological laws can be deduced from them. For the elucidation of such laws, it is necessary to carry out metabolic experiments by which the transformation of energy and material within the body can be studied with some degree of precision.

Energy transformation can only be studied by some form of calorimetry where the heat output of the body can be measured, and, in the study of the whole material exchange, account must be taken, not only of the urine and faeces, in which the mineral elements and the end-products of protein metabolism are excreted, but also of the gaseous exchange, which is the chief means for the elimination of carbon and for the intake of oxygen. For a complete balance experiment, therefore, some form of respiration calorimetry is required.

Calorimetric determinations upon farm animals have been made by Kellner, Zuntz, Hageman, Armsby, Møllgaard and Andersen, and others, to whom we are largely indebted for what exact knowledge we have of the energy exchange in these animals. In Britain, until recently, this line of investigation has been avoided by agricultural research workers on account of the difficulty in obtaining the apparatus considered necessary. A description of the very costly and highly complicated modern chamber calorimeter is sufficient to deter the average worker from attempting this line of research.

At the Cambridge School of Agriculture, a simple form of calorimeter has been constructed by Capstick (1). It registers the heat output, but no account is taken of the gaseous exchange. It has the great advantage that it can be controlled by one worker. Further, the cost of installation is relatively low; it can be fitted up for less than £500. This simplified

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form of calorimeter has proved a very valuable instrument, and important work on basal metabolism has already been done (Capstick and Wood (2 and 3)).

In the respiration chamber calorimeter, the heat output is measured directly, and, in addition, the oxygen consumption and carbon dioxide production are also determined. From these, the amount of heat evolved can be determined indirectly by calculation. The results of these two methods, the direct and the indirect, as has been proved by Rubner, Lusk and others, agree closely. In a series of 22 experiments on the dog, Murlin and Lusk (4) found that the average heat output calculated by the indirect method was 2244 calories. The amount registered by the direct method was 2230, a difference of less than one per cent.

In recent years, in working with human subjects, the chamber calorimeter has been largely superseded by various types of apparatus by means of which the gaseous exchange only is determined, and, from the oxygen consumption and the carbon dioxide output, the heat evolved is calculated. An account of the various methods in use is given by Carpenter (13) and by Krogh (12). In all the different forms the respired air is collected by some sort of a mask or mouthpiece. Zuntz and Hageman used the indirect method in work with horses, and Møllgaard and Andersen (5) with milk cows. These workers collected the expired air by means of a canula inserted into the trachea.

This indirect method has several advantages over the chamber method. The apparatus is light and can be carried about, so that determinations can be made in almost any environment. Further, the exhaled gases, instead of being mixed with the air of the chamber, are collected direct without dilution. The results are therefore clearer, and determinations can be made over short periods, so that successive changes in the rate of heat production, in the respiratory quotient, and in the rate of methane excretion, can be traced under the different conditions that affect metabolism, such as feeding, muscular exercise, or change of external temperature. It is obvious that a simple method of indirect calorimetry applicable to ruminants opens up a wide and interesting field of investigation.

PRINCIPLES ON WHICH INDIRECT CALORIMETRY DEPENDS.

A lucid exposition of the principles upon which indirect calorimetry depends has been given by Lusk (6) and Magnus-Levy (7). It is therefore unnecessary to give here more than a brief outline which will enable the method described below to be understood.

Energy developed in the body is evolved by a process of oxidation. In the complete oxidation of a given quantity of material of constant composition, a definite amount of oxygen is used, a definite amount of carbon dioxide produced, and a definite amount of heat evolved. The following tables of values, which are those given by Loewy (cited by Lusk, *loc. cit.*), shows the relationship of these values in the case of the energy-yielding constituents of food.

Table I.

One gram	O ₂ consumed c.c.	CO ₂ produced c.c.	Total heat liberated. Calories	Calories per litre O ₂ .
Carbohydrate (starch) ...	828.8	828.8	4.182	5.047
Fat ...	2019.3	1427.3	9.463	4.686
Protein ...	966.3	773.9	4.316	4.485

It will be seen from the table that the heat production per litre of oxygen varies in the case of the three food constituents. In indirect calorimetry the *total* amount of oxygen absorbed, and of carbon dioxide produced are determined. Before their heat value can be calculated, therefore, it is necessary to know in what proportions the three substances have been oxidised during the experimental period.

In an experiment of sufficient length the amount of protein oxidised can be calculated from the amount of nitrogen in the urine. It is thus possible to determine what amounts of oxygen and of carbon dioxide in the total amount are due to the protein. The remaining amounts are due to carbohydrate and fat.

When carbohydrate is oxidised, the volume of oxygen consumed equals the volume of carbon dioxide produced. Therefore the ratio $\frac{\text{vol. of CO}_2 \text{ produced}}{\text{vol. of O}_2 \text{ consumed}}$, known as the respiratory quotient (R.Q.), is unity.

When fat is oxidised, oxygen is required for the oxidation of hydrogen as well as for carbon. Hence the volume of oxygen consumed is greater than that of carbon dioxide produced. According to the above table,

the R.Q. is $\frac{1427.3}{2019.3}$, i.e. 0.707 approximately. If, therefore, only carbo-

hydrates are consumed, the R.Q. will be unity; if only fat, 0.707. The level of the R.Q. between these limits indicates the proportion of the two substances utilised, *e.g.*:

R.Q.	Carbohydrate per cent.	Fat per cent.
0.707	0	100
0.80	32	68
0.90	66	34
1.00	100	0

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The R.Q. for proteins is 0.801 (Loewy, *loc. cit.*), *i.e.* intermediate between fat and carbohydrate. The oxygen consumption due to oxidation of protein in short experiments is so small that in practice it is ignored, the calculation being confined to carbohydrate and fat. Magnus-Levy(7) has shown that the error involved in neglecting to make separate calculation of the protein metabolism is very small, varying in amount to three per cent.

Zuntz and Schumburg have compiled a table (Table II, Appendix, from Lusk, *loc. cit.*), showing the calories produced for one litre of O_2 consumed for different R.Q.'s. In practice, when the total O_2 consumed and CO_2 produced are known, the R.Q. is calculated, and then by multiplying the number of litres of O_2 consumed by the factor corresponding to the R.Q., the heat produced is obtained.

THE APPLICATION OF THE INDIRECT METHOD TO RUMINANTS.

In applying the indirect method of calorimetry to ruminants two difficulties are encountered: (1) the collection of the expired air, and (2) the presence of gases of fermentation in the expired air.

APPARATUS.

Collection of Expired Air. The expired air must be collected either by a canula inserted into the slit trachea, or by a mask that can be adjusted over the muzzle so that there is no leakage and no discomfort to the animal. The canula or mask must be fitted with an inlet valve, which allows the entrance of atmospheric air during inspiration and is closed during expiration; and with an outlet valve which is closed during inspiration, and during expiration diverts all the expired air to a collecting bag. The valves must be so easily moved that a very slight difference in pressure on the two sides is sufficient to open or close them.

Fig. 1 shows in position a mask with two such valves. The upper part of the mask consists of a broad tube of thin rubber, about two inches in diameter, with a side tube and valve so that it can be inflated. To it is attached a muzzle-shaped part of stout rubber carrying the two valves, one at the end, and one above. When the mask is fitted to the head, the broad tube is inflated, and the part of the tube next the face is lightly smeared with vaseline to prevent leakage. The mask is held in position by elastic bands which pass round the horns. No great tension is required either in the rubber tube or in the bands. A tension sufficient to hold the mask in position will prevent leakage.

The valve used consists of a turned brass disc, about 2 mm. thick and 3.5 cm. in diameter, bored in the centre to take a 1.5 cm. brass tube, which is soft-soldered into it. The end of the tube and the disc are then turned flush, leaving a raised valve face, 0.5 mm. broad and 0.5 mm. high, round the mouth of the tube. Over this ridge (Fig. 2, *b*) the thin rubber disc is stretched. The tube is about 1.5 cm. long and is screwed at the free-end to take a brass ring which clamps it in the mask (Fig. 4, *d*).

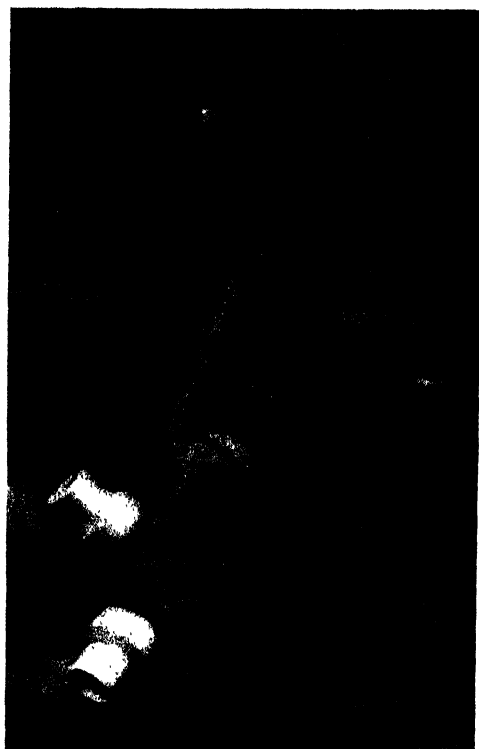


Fig. 1. Showing mask in position.

Fig. 3 shows the disc and the three equidistant points of attachment of the rubber by means of shellac. The valve is shown in position in cross-section in Fig. 4. The thick rubber of the mask is gripped between an aluminium base piece (*a*) and an outside ring (*b*), which is held in position by the aluminium nozzle (*c*) which screws on to the base piece. The valve is clamped by the ring (*d*) which screws tightly against (*a*), and the rubber

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washer (*w*) prevents leakage. The same valve is used as both inlet and outlet; its position is reversed inside the inlet nozzle of the mask.

From the outlet valve a corrugated rubber tube passes to the collecting bag. That used by the writers is a Douglas bag fitted with a three-way aluminium cock, which communicates either with the external

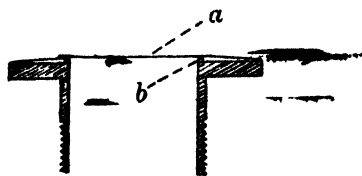


Fig. 2. Cross section of valve.
a. Thin rubber disc. *b.* Raised valve face.

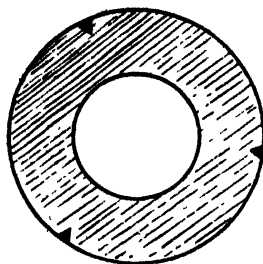


Fig. 3. Plan of valve, showing points of attachment of rubber disc.

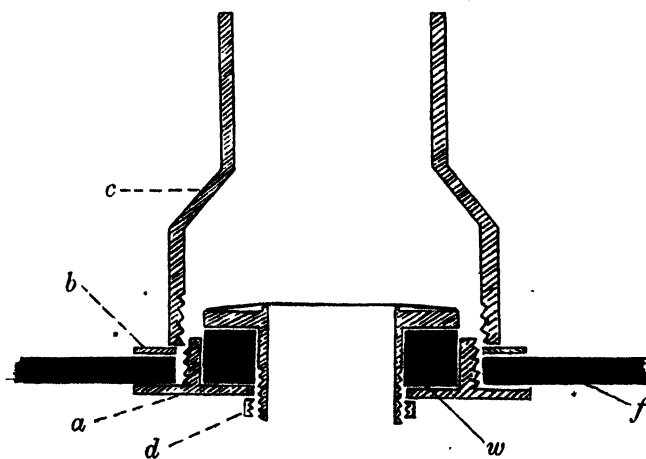


Fig. 4. Cross section of valve in position.

- | | | |
|---------------------------------|-----------------------------|---------------------------|
| <i>a.</i> Aluminium base piece. | <i>c.</i> Aluminium nozzle. | <i>f.</i> Rubber of mask. |
| <i>b.</i> Outer ring. | <i>d.</i> Ring. | <i>w.</i> Rubber washer. |

air or with the bag. The cock is turned to carry the expired air to the bag at the beginning of the period of collecting the sample, and is turned to carry it to the outside again at the close of the period.

Analysis of Expired Air. The instrument used for the analysis of the expired air is a modification of Haldane's apparatus. A description of the apparatus, and of the method of analysis, is given by Haldane (8) and

by Cathcart (9). Fig. 5 gives a general idea of the nature of the apparatus. The sample of air to be analysed is drawn into the burette *A*, and the amount measured. The CO_2 is absorbed by passing it over KOH (10 per cent.) in the bulb *E*. The decrease in the volume of the sample after this operation indicates the amount of CO_2 present.

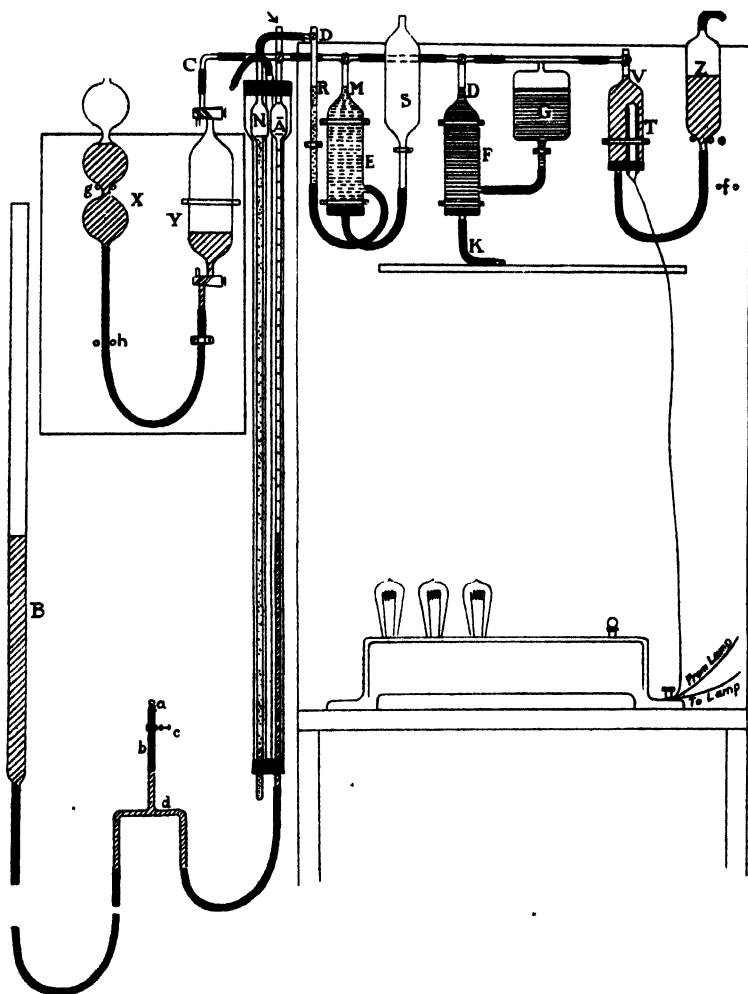


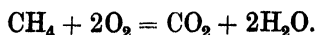
Fig. 5. Apparatus for gas analysis.

The remaining gas is then passed over to bulb *T*, and, by the passing of a current of electricity through a platinum wire, the combustible gases

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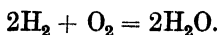
are oxidised. The amount of CO_2 produced in the combustion is estimated by passing the gas again over the KOH in *E*.

In the oxidation of one volume of methane two volumes of oxygen are used, and one volume of carbon dioxide produced.



The H_2O condenses, and, as the gases being analysed are always saturated with vapour, the water makes no difference to the volume. Therefore, on combustion, after the CO_2 produced has been absorbed, the reduction in volume is three times the amount of methane present, and three times the amount of CO_2 produced.

In the case of hydrogen, if it were present, two volumes of hydrogen would require one volume of oxygen for its combustion, and no CO_2 would be produced.



There would therefore be no reduction in volume when the gas, after combustion, was passed over the KOH .

After the estimation of the CO_2 and the combustible gases the gas is passed over alkaline pyrogallate solution in the bulb *F*, where the oxygen is absorbed. The reduction in volume shows the amount of oxygen present. To this amount, of course, must be added the oxygen which was used in the combustion of the methane, *i.e.* $\frac{2}{3}$ of the total decrease in volume after the absorption of CO_2 produced by the combustion of the CH_4 .

The passing of the gas from the bulb *A* to the various other bulbs is effected by manipulation of the taps, and of the mercury levelling tubes *B* and *Z*, the latter being used when the gas is being passed into the combustion tube.

The chief modifications made by the writers on the original type of apparatus are as follows. The tap on burette *A* has a right-angled bore, so that, in loading the burette from the sampling tube *Y*, the connections can be flushed out by having the gas in *Y* under pressure by raising the mercury bulb *X*, with the tap turned so that the tube from *Y* is connected to the outside air at the arrow. After the connections have been flushed out, a sample of the air to be analysed can be passed into the burette by turning the tap through 90° , and then lowering the levelling tube. It can then be connected to the series of bulbs by turning it through a further 90° . A description of the method of loading the burette *A* by means of this tap and the stand seen in the diagram with the sampling

tube in position has already been given by Cathcart (*loc. cit.*), with whom one of us was working when this modification was devised.

The bulb *G*, which provides space for the displaced pyrogallate when the air is passed over to the bulb *F*, contains liquid paraffin which floats on the surface of the pyrogallie solution and excludes air. This is simpler than the system of bulbs adopted by Haldane, and is as effective. Cleaning is easier, and the liability to breakage is much reduced.

Other modifications, such as the taps, the shape of the bulbs and the method of making fine adjustments, *a*, *b*, *c*, *d*, are of minor importance. Haldane's apparatus is a fascinating instrument to work with, and every worker is certain, sooner or later, to make slight adjustments and alterations for his convenience.

PROCEDURE IN CONDUCTING AN EXPERIMENT.

Before beginning to carry out experiments it is necessary to have a number of preliminary trials to get the animal accustomed to the mask and other apparatus. Some of the goats with which the writers worked required only a few days' preliminary trials; others needed to have blank experiments carried out for nearly a fortnight before they settled down sufficiently to remain still while the samples of expired air were being taken.

In drawing off a sample, the mask is first adjusted and fixed; the outlet valve of the mask is then connected to the three-way cock of the collecting bag by means of the detachable corrugated tube. It is advisable at this stage to test the apparatus for leakage. If the thumb be placed over the outlet of the three-way stop-cock of the collecting bag, the pressure will rise, when the animal respire, and any leakage is easily detected. In adjusting the apparatus for the first time, a thorough examination for leaks should be carried out, a lather of soap being applied to all possible points of escape.

After the animal has been for a few minutes in the position required for the experiment, *e.g.* standing or lying, the cock is turned so that the expired air passes into the bag. After a suitable period, usually about 10 minutes, the cock is turned to allow the expired air to escape, and the collection is finished.

The amount of the expired air collected is then measured by passing it through a gas meter. The flexible tube attached to the bag is transferred from the mask to the meter, and the bag emptied by gentle and steady pressure.

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The temperature of the air as it passes through the meter, and the barometric pressure, are noted. These are required for the calculations.

While the air is being measured a sample from the bag is taken into a Bohr's sampling tube (Y, Fig. 5) for analysis. The levelling bulb is raised so that the tube is filled with Hg. The tube is connected with the Douglas bag by means of the side tube. Then by lowering and raising the bulb several times, the connections are washed free from atmospheric air. The tube is then filled by lowering the bulb. As a correction for this air, which is not passed through the meter, 100 c.c. (the capacity of the sampling tube) are added to the total registered by the meter. According to the nature of the work, the analyses will be made immediately after taking the sample, or, if the experiments follow each other closely, the samples will be reserved and analysed when convenient.

The foregoing description is intended to give only a general idea of the method. The details of the procedure in collecting and analysing samples are given by Cathcart (*loc. cit.*).

THE ANALYTICAL DATA.

The expired air in the ruminant differs in composition from the inspired air as follows:

Added methane	}	from fermentation.
Added carbon dioxide		
Added carbon dioxide	}	from tissue metabolism.
Diminished oxygen		

Reasons are adduced later for believing that methane is the only combustible gas present in appreciable quantities. The data obtained by the methods described show:

- (1) the volume of air expired during the experimental period;
- (2) its temperature, and the barometric pressure when it was measured;

- (3) the percentage of methane, carbon dioxide and oxygen present.

To estimate the heat output it is necessary to determine from these data the absolute amounts, dry, at 0° C. and 760 mm. pressure of

- (1) methane produced;
- (2) CO₂ produced in the tissues as distinct from CO₂ produced by fermentation;
- (3) the oxygen absorbed in the tissues.

Table III (Appendix), (Haldane(8)) gives the factors for the reduction to standard temperature and pressure of expired air measured at different initial temperatures and pressures.

CALCULATION OF RESULTS.

I. *Fermentation.* CH_4 and CO_2 produced by fermentation. The percentage of CH_4 present is known from the analysis. The absolute amount can therefore be calculated directly. Krogh(12) has shown that in the fermentation in the paunch of the ruminant, the ratio of methane to CO_2 produced is approximately 1 : 2.6, so that 2.6 times the amount of methane equals the CO_2 produced by fermentation.

II. *Tissue Metabolism.* O_2 consumed and CO_2 produced in the tissues. The amount of O_2 consumed in the tissues and the amount of the CO_2 produced is the difference between the amounts of them in the inspired and expired air. The amount in the expired air is known, since the volume has been measured and its percentage composition determined by analysis. In the inspired air the percentage of oxygen and that of carbon dioxide are constant, 20.93 and 0.03 respectively. But the volume of the inspired air has not been measured, and it cannot be taken to be the same as that of the expired air, since the amount of oxygen consumed does not necessarily equal the amount of carbon dioxide and methane produced. It can however be calculated. The amount of nitrogen is unchanged in the gaseous exchange. Therefore the volume of the inspired air = the vol. of expired air $\frac{\text{per cent. of } \text{N}_2 \text{ in expired air}}{\text{per cent. of } \text{N}_2 \text{ in inspired air}}$. The percentage of nitrogen in the expired air is 100 minus the total of the percentages of oxygen, carbon dioxide and methane. In the inspired air it is 79.04 per cent.

By one or other of various methods based on these principles, the total oxygen consumed and carbon dioxide produced during the experimental period can be calculated. The amount of CO_2 arising from tissue metabolism is the total CO_2 , less the CO_2 of fermentation as calculated above.

III. *Calculation of the Heat Output.* (a) *Fermentation Heat.* Krogh has shown that in the fermentation in the rumen, for every litre of methane produced 3.97 calories are evolved. Hence the heat of fermentation equals the volume of methane in litres, multiplied by 3.97.

(b) *Tissue Heat.* To calculate the heat output from tissue metabolism, the R.Q., i.e. $\frac{\text{CO}_2 \text{ produced in the tissues}}{\text{O}_2 \text{ consumed}}$, is found. Table II shows the

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figures by which the volume of oxygen must be multiplied to give the amount of heat evolved in the tissues.

The addition of tissue heat and fermentation heat gives the total heat output of the animal for the period during which the sample of expired air was collected.

EXAMPLES OF RESULTS OBTAINED.

During the past three years the method of indirect calorimetry has been used by the writers in investigations on the goat. The influence on the rate of metabolism of muscular exercise, food, external temperature, and pregnancy have been determined, and some factors controlling the production of methane have been investigated. The results of this work, some of which is still in progress, will be published in due course. The following examples illustrate the nature of the results obtained.

Variation in different experiments. Variations are found in the rate of metabolism in the same animal under experimental conditions, which, in as far as they can be controlled, are identical. Thus, even in successive experimental periods, separated only by a few minutes, a considerable difference in the rate of metabolism may be obtained. These differences are due chiefly to muscular activity, either during, or immediately preceding the experimental period. Even though the muscular activity may not appear as visible muscular movements, it may still affect the rate of metabolism. Increased tonus with little or no movement, causes a distinct rise in the rate of metabolism. Cathcart and Orr (10) found that a soldier standing "at attention" had an energy expenditure of 53.1 calories per sq. metre per hour, compared with 45.6 when standing "at ease," even though in both cases there was no visible movement. In the case of the goat, the reaction to external stimuli such as noises, or the appearance of strangers, causes an immediate rise in the rate of metabolism. In some of the experiments carried out with the goat in the lying position, the animal appeared to go to sleep. In them the rate of metabolism was lower than in others when the animal was in the same position, and as motionless, but awake.

These variations point to real variations in the rate of metabolism, and as such, give valuable information as to the fluctuations which occur in the rate of heat production. The fact that these variations do occur, however, makes it necessary when investigating the influence of other factors that affect metabolism, such as food, work, and temperature, to do a number of experiments and compare averages, instead of individual results.

The results in the following table are obtained from the same animal, under as far as possible identical conditions as to feeding and environment. Three samples were taken on the same day with an interval of from half an hour to an hour between the times of sampling.

Table IV. *Showing variation in the rate of tissue metabolism.*

Date	Time of sampling	R.Q.	Tissue metabolism. Cal. per hour
31. iii. 23	8.38- 8.44 a.m.	0.77	42.6
	9.30- 9.40 a.m.	0.75	42.8
	10.27-10.33 a.m.	0.73	46.1
2. iv. 23	8.44- 8.50 a.m.	0.72	48.4
	9.25- 9.35 a.m.	0.72	42.8
	9.59-10.05 a.m.	0.79	46.4

The shorter the experimental period, the greater is the extent of the variation likely to be found. It is advisable for this reason, to have the experimental periods as long as possible. It is under exceptional circumstances only that less than 10 minutes' collections should be taken.

Standing and Lying. The following figures give an idea of the increase in energy expenditure in standing, compared with lying. The experiments in each pair were performed on the same goat, with only a short interval between them.

Tissue metabolism in calories per hour.

	Lying	Standing
A	61.2	64.6
B	60.1	65.0
C	52.1	63.6
D	44.3	50.8

The average increase in energy expenditure in standing as compared with lying is, according to these results, about 12 per cent. Cathcart and Orr (*loc. cit.*) found that in man the increase was about 13 per cent. when standing at ease, *i.e.* with muscles relaxed, and 34 per cent. when standing at attention. The quadruped evidently expends a similar amount of energy in standing to the biped. The interesting question of the expenditure of energy of the goat in inanition as compared with man will be dealt with in a later paper.

Food. The influence on the rate of metabolism of feeding is illustrated by the following figures.

Tissue metabolism in calories per hour. Animal on mixed diet.

Before feeding (12 hours after last meal)	Half hour after feeding
45.6	56.2
43.8	52.3
44.6	51.6
46.2	50.2

Table III. *Table for Reduction to dry air at 0° C. and 760 mm. of 100 volumes of air saturated with moisture at different temperatures and pressures.*

Temp. °C.	Barometric pressure in millimetres								
	740	745	750	755	760	765	770	775	780
10	92.77	93.39	94.04	94.66	95.30	95.93	96.57	97.21	97.84
11	92.36	92.98	93.63	94.25	94.89	95.52	96.16	96.79	97.42
12	91.95	92.55	93.18	93.80	94.44	95.07	95.70	96.33	96.96
13	91.54	92.17	92.80	93.41	94.05	94.68	95.31	95.94	96.57
14	91.13	91.76	92.38	93.00	93.62	94.26	94.88	95.51	96.13
15	90.71	91.34	91.96	92.57	93.20	93.82	94.44	95.08	95.70
16	90.29	90.92	91.54	92.15	92.78	93.40	94.01	94.64	95.26
17	89.87	90.50	91.11	91.72	92.35	92.97	93.58	94.21	94.83
18	89.45	90.08	90.68	91.30	91.92	92.54	93.15	93.71	94.39
19	89.02	89.64	90.25	90.86	91.48	92.09	92.71	93.32	93.94
20	88.59	89.21	89.81	90.41	91.04	91.65	92.26	92.88	93.50
21	88.18	88.86	89.40	90.01	90.62	91.23	91.84	92.45	93.07
22	87.71	88.32	88.90	89.53	90.14	90.75	91.36	91.97	92.60
23	87.26	87.87	88.47	89.08	89.69	90.29	90.90	91.51	92.13
24	86.61	87.43	88.01	88.62	89.23	89.83	90.44	91.04	91.65
25	86.35	86.96	87.57	88.17	88.79	89.38	89.98	90.57	91.17

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NOTES ON THE DRAINAGE FROM TOWER SILOS.

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IN a recent paper dealing with the changes which occur during the ensilage of oats and tares, Amos and Woodman⁽¹⁾ indicate that drainage is an important source of loss during ensilage and record that the drainage liquid has been found to contain varying quantities, between 4 and 10 per cent., of soluble material. No analysis of this soluble material is given.

During the summer of 1922 samples of the drainage liquid from three concrete silos in the north of Scotland were collected and analysed, particular attention being paid to the mineral ingredients present. In one case it was possible to measure the rate of flow of the drainage practically from the time that it first issued from the silo up to the time when it had almost ceased to flow and thus the total losses from this source during ensilage could be calculated.

The silo at this Institute is 12 feet in internal diameter and built to hold about 110 tons. The crop used was a mixture of beans, peas, oats and tares, sown at the rates of 1 bushel, $1\frac{1}{2}$ bushels, 3 bushels, and $\frac{1}{2}$ bushel per acre respectively. It was moderately mature when cut by a binder on August 7 and 8 and filled straight into the silo, about 100 tons in all being put in. The drain at the base did not function but, on the morning of August 10, liquid began to ooze out at the bottom door boards. It was collected by fixing an outer board on to the step and passing through this an iron pipe. The flow had practically ceased on September 1 and collections for analysis were then stopped. The rate of flow was measured by collecting the liquid for two hours at the same time each day.

The total dry matter in these samples was estimated by evaporating 50 c.c. of the liquid and drying the residue to constant weight in a steam oven. Nitrogen was estimated by the Kjeldahl method and all the mineral constituents were estimated in the ash. The acids, volatile and non-volatile in steam, were estimated in a number of samples.

The average rate of flow and composition of the drainage liquid at different stages are given in Table I.

Table I.

100 gallons of the liquid contain

Days after filling	Average flow in gallons per 24 hours	Dry matter lbs.	Ash lbs.	CaO lbs.	P ₂ O ₅ lbs.	SO ₃ lbs.	K ₂ O lbs.	Crude protein (N × 6.25) lbs.
4-6	44.3	85.7	15.7	2.54	1.23	0.219	0.824	22.8
7-9	28.1	80.7	15.4	2.65	1.27	0.212	0.801	23.7
10-18	15.0	79.4	15.7	2.75	1.32	0.231	0.803	24.7
19-23	6.15	79.7	15.8	2.83	1.33	0.224	0.803	25.2
24	3.87	80.4	15.7	2.88	1.32	0.234	0.803	25.4

On the average the liquid contained volatile acids equivalent to 0.45 per cent. of acetic acid and non-volatile acids equivalent to 0.60 per cent. of lactic acid.

It will be seen that after the first three or four days the total dry matter in the liquid remained practically constant, and contained from 26-32 per cent. of crude protein and 18-20 per cent. of ash. The ratio of CaO : P₂O₅ remained practically constant at 2.1 : 1 and the amounts of both of these ingredients present in the drainage liquid rose slightly but steadily as drainage proceeded.

The total losses from this silo, by drainage, for the period during which any appreciable quantity of liquid was draining away are given in Table II.

Table II.

Days after filling	Total vol. of drainage gallons	Dry matter lbs.	Ash lbs.	CaO lbs.	P ₂ O ₅ lbs.	SO ₃ lbs.	K ₂ O lbs.	Crude protein lbs.
4-6	132.9	113.9	20.86	3.37	1.63	0.29	1.09	30.30
7-9	84.3	68.0	12.98	2.23	1.07	0.18	0.68	19.98
10-18	135.0	107.2	21.19	3.71	1.78	0.31	1.08	33.34
19-23	24.6	19.6	3.88	0.69	0.33	0.05	0.20	6.20
24	3.9	3.1	0.61	0.11	0.05	0.01	0.03	0.99
Totals for 21 days	380.7	311.8	59.52	10.11	4.86	0.84	3.08	90.81

The silage from which this drainage was obtained had a pleasant, slightly acid smell and was of the acid, light-brown type, according to the classification of Amos and Williams(2). It was readily eaten by the stock. It contained 27.05 per cent. of dry matter, 2.41 per cent. of crude protein, 1.47 per cent. of ash, 0.28 per cent. of CaO and 0.165 per cent. of P₂O₅. Assuming that 100 tons of silage were made the percentage losses of the various ingredients due to drainage during the twenty-one days would be: dry matter 0.51 per cent., ash 1.80 per cent., crude protein 1.7 per cent., CaO 1.6 per cent., P₂O₅ 1.3 per cent.

The other two silos, samples of the drainage from which were analysed, were on the farms of Mr J. Cruickshank, Port Erroll. One of these silos (at Ardmachron) holds about 160 tons and the other (at Errollston) about 200 tons. They were mostly filled on wet mornings when no work could be done among the hay.

The first silo, at Errollston, was filled one-third full of a mixed crop of clover and rye-grass between July 13 and August 2, 1922. A sample of the drainage liquid coming through the door boards was taken on August 8 after it had been running for 14 days (Sample *A*, Table III). The filling of this silo was recommenced on August 18 and completed on September 3 with a mixture of beans, peas, oats and tares which were somewhat immature and had not been allowed to wilt. The material was thus very "sappy," and also had a considerable amount of external moisture. The drainage liquid was flowing very rapidly from the upper doors of this silo on September 4 when a sample (*B*, Table III) was taken. The liquid was then draining away at the rate of 823 gallons in 24 hours, and came almost entirely from the tares mixture, the clover and rye-grass being too densely packed at the base to allow of much percolation through it.

The second silo, at Ardmachron, was filled between August 14 and September 7 with a mixture of beans, peas, oats and tares which had been sown at the rates of 3 bushels, $\frac{1}{2}$ bushel, 2 bushels, and $\frac{1}{2}$ bushel per acre respectively. The liquid commenced to flow from the doors of this silo on August 25 and on this date a sample (*C*, Table III) was taken. Further samples were taken on August 31 (*D*) and September 6 (*E*).

The composition of the drainage liquid from these two silos is given in Table III.

Table III.

100 gallons of the liquid contain

Sample	Dry matter lbs.	Ash lbs.	CaO lbs.	P ₂ O ₅ lbs.	SO ₃ lbs.	K ₂ O lbs.	Crude protein lbs.
ERROLLSTON SILO							
<i>A</i>	67.54	14.03	2.91	0.85	0.13	1.02	11.75
<i>B</i>	47.02	10.49	1.40	1.01	0.13	0.84	14.52
ARDMACHRON SILO							
<i>C</i>	53.87	12.91	1.04	1.13	0.13	1.18	14.78
<i>D</i>	67.06	16.00	1.60	1.37	0.16	1.34	19.55
<i>E</i>	61.74	13.98	1.48	1.17	0.15	1.25	18.17

Sample *A* contained volatile acids equivalent to 0.85 per cent. of acetic acid and non-volatile acids equivalent to 0.63 per cent. of lactic

acid. The acidity was not determined for the other samples. Calculated on the rate of flow when sample *B* was taken on September 4 the total loss from the Errollston silo, at that time, during 24 hours would be 823 gallons of liquid containing 387 lbs. of dry matter, 86.33 lbs. of ash, 11.5 lbs. of CaO, 8.3 lbs. of P_2O_5 , 1.07 lbs. of SO_3 , 6.9 lbs. of K_2O and 119.5 lbs. of crude protein. The rate of flow from this silo would undoubtedly drop off fairly rapidly, but even so, the loss of material over a period of 2-3 weeks would be very considerable being as it was greater for the 24 hours than the total loss during 21 days from the Institute silo. This excessive drainage and high percentage loss of dry matter was undoubtedly due to the "sappiness" of the green crop as put into the silo. This is in accord with the finding of Amos and Woodman that "whilst green, fruity silage of an excellent quality was obtained by preserving the unwilted, immature forage, yet the excessive drainage, consequent on 'sappiness,' led to a needlessly high percentage loss of dry matter."

A comparison of the four types of drainage liquid is given in Table IV on the basis of the percentage composition of the dry matter in the liquid.

Table IV. *Composition of the dry matter of the drainage liquid.*

Silo	Crude protein %	Ash %	CaO %	P_2O_5 %	SO_3 %	K_2O %	Ratio CaO : P_2O_5
Institute	29.1	19.1	3.24	1.55	0.27	0.99	2.1
Errollston <i>A</i>	17.4	20.8	4.31	1.26	0.19	1.51	3.4
Errollston <i>B</i>	30.8	22.3	2.97	2.15	0.28	1.78	1.4
Ardmachron (mean of <i>C</i> , <i>D</i> and <i>E</i>)	28.7	23.4	2.25	2.00	0.24	2.07	1.1

The most marked differences between the different liquids considered in this way are (*a*) in the crude protein where the percentages vary as widely as 17.4 and 30.8, and (*b*) in the ratio CaO : P_2O_5 where the variations are as wide as 3.4 and 1.1. The differences are mainly between the two samples from the Errollston silo and are undoubtedly due to the different crops used. It is of interest, however, to note the differences in the ratios of CaO : P_2O_5 and the percentages of potash in the dry matter of the drainage liquids from the Institute silo and the Ardmachron silo. The crops in each case were beans, peas, oats and tares, but the mixtures were sown in different proportions and the soils were different. That at the Institute is a medium loam, whilst that at Ardmachron is a stiff clay having plenty of available potash.

All the results indicate a material loss of nitrogenous substances and of mineral ingredients in the drainage liquid. The loss of the mineral

ingredients is of importance if the silage is to be fed to growing stock or milking animals, both of which need adequate supplies of calcium, phosphorus and potassium in their foods. It is desirable, therefore, that losses in this direction should be reduced to a minimum. This loss of mineral ingredients, which may amount to nearly 2 per cent. of that present in the green crop, should be borne in mind in comparing the nutritive value of oats and tares when made into hay or made into silage. If the hay is cured in fine weather there should not be any loss of mineral matter.

The writer desires to express his thanks to Mr James Cruickshank for his kindness in supplying him with the samples of drainage from his silos, and with details of the crops, dates of filling, etc.

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- (1) AMOS and WOODMAN (1922). *Journ. Agric. Sci.* **12**, 337.
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ON THE EFFECT OF WEAR ON SMALL MESH WIRE SIEVES.

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(With Plate V and Nine Text-figures.)

INTRODUCTION.

THE use of sieves of fine aperture for the separation and grading of material is very widespread in industry. Thus, bolting-silk of extremely fine mesh is used in the flour industry, while the employment of fine wire sieves for the grading to specification of basic slag, etc., and for part of the routine involved in the methods of mechanical analysis of soils, will be familiar to agriculturists.

The present investigation was undertaken owing to some anomalous results with a sample of basic slag which seemed to depend upon the sieving process obtained in the Chemical Department of this Station, and the examination has been extended to include new sieves, and others that have been used for mechanical analysis for varying periods¹.

The main objects were, in the first place, to measure the uniformity of new sieves with respect to the linear dimensions and area of the holes, and the diameter of the wire; and secondly, to compare with these the corresponding measurements of used sieves, so as to gain some idea of the change in size of the holes brought about by wear.

EXPERIMENTAL.

The measurements were made with a microscope provided with an objective of low magnification and considerable depth of focus, with a graduated scale in the focal plane of the eyepiece.

In the case of new sieves and others needed afterwards, the microscope was mounted so that it could be traversed across the sieve; in the case of disused sieves, a suitable portion was cut out and mounted direct on the mechanical stage of the microscope.

The measurements were made by recording the points where the image of the left and right sides of successive strands of wire crossed the eye-

¹ Some of the sieves examined were in use at Rothamsted, the remainder were kindly supplied by workers elsewhere.

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piece scale. The sieve was then moved sideways for the appropriate distance and the observations continued. The measurements made in this manner enabled both the dimensions of the wire and the mesh to be obtained.

Measurements were made in this manner, (a) on single rows of meshes extending across the sieve, both warp and weft directions being used in this series, and, (b), of small square patches of the sieve. The measurements were so recorded that the linear dimensions of any given square were easily picked out from the experimental data in order that the appropriate figures should be used in calculating the area of the meshes.

A certain amount of discrimination had on occasion to be used in estimating the point where the wire image crossed the eyepiece scale. The strands of wire are, of course, bent for some distance on either side of the point where warp and weft cross, and unless this bending happens to be in a plane passing through the optical axis of the microscope, and parallel with the division marks of the scale, the wire appears effectively thicker than its true width. In the preliminary measurements, where an objective of small depth of focus was used, this effect showed itself in a lack of focus of one side of the wire. The use of an objective of a greater depth of focus was a considerable help in obtaining a fair estimate of the diameter of the wire, although this judgment needs some correction when the third dimension of the sieve lattice is taken into account.

The magnification employed throughout the measurements was 30 diameters. The results have been plotted as frequency diagrams in which the readings expressed as a percentage of the total number have been grouped according to the percentage deviation from standard. The interval covered by each group varies slightly for different sets of readings, being between 5 and 7 per cent. for aperture readings, and about 3 per cent. for the wire diameters. Smooth curves have been drawn through the points instead of joining them, as this makes it easier for the eye to take in the salient features.

DISCUSSION OF RESULTS.

Sieve I (Fig. 1, *B* and *C*; Fig. 2, *A* and *C*). This was a new unused "100 mesh" sieve woven according to the I.M.M. specification, *i.e.* the diameter of the wire employed ($\cdot 01$ ") was equal to the side of the square holes between the wires. It was woven so that each strand passed, not over one wire and under the next, but over two wires and then under the next two. We shall refer to these two types of weaving as single and double weave respectively. The latter is illustrated in Plate V, figs. A and

B. Fig. A was obtained with both back and front illumination of the sieve, and shows the relation of the wires to one another. A clearer idea of the nature of this form of weaving is given in Fig. B, photographed with no back illumination, so that only the front of the sieve is shown. The wires of one system will be seen passing over two of the other system at right angles, and in addition it will be noted that extra strength is gained by the successive one-hole displacement of the first system.

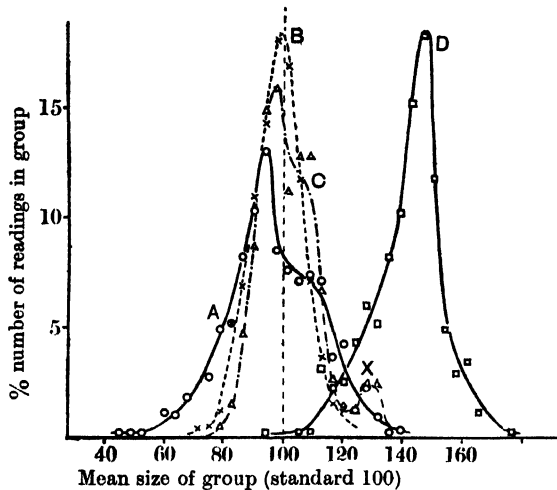


Fig. 1. Double weave.

o □, A and D. Old sieve—spaces, warp and weft.
 Δ ×, B and C. New “ “ “

On this sieve, in view of its obvious uniformity, a full measurement of a patch 24×25 meshes was made, involving 2400 readings. These figures, when suitably combined, gave results for (a) diameter of wire of both warp and weft, (b) linear dimensions of spaces in warp and weft directions, (c) area of spaces. In Fig. 1 (B and C) are given, on the same scale, frequency curves for the aperture dimensions in the two directions, and in Fig. 2 the variation in diameter of the wire (C') and aperture area (A).

The diameter of the wire readings for the two directions were indistinguishable and have been combined. The four curves may be taken as an indication of the degree of uniformity to be expected in a new sieve woven to the I.M.M. specification. The peaks of all the curves fall practically on the vertical dotted line representing the specification standard, as they should do if the linear dimensions of the holes are equal to the diameter

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of the wire. The frequency curve for the diameter of the wire has a slightly wider spread than those for the wire of used sieves (*cf. D and E, Fig. 2*). This is due to the fact that the wires straighten out with wear, and the experimental error in reading a crinkled wire is naturally greater. The spread of the frequency curve for the hole diameters in each direction is within reasonable limits. Attention is drawn to the secondary maximum marked *X* in curve *C, Fig. 1*. This is due to one strand of wider spacing than the others, which it was possible to pick out by visual examination.

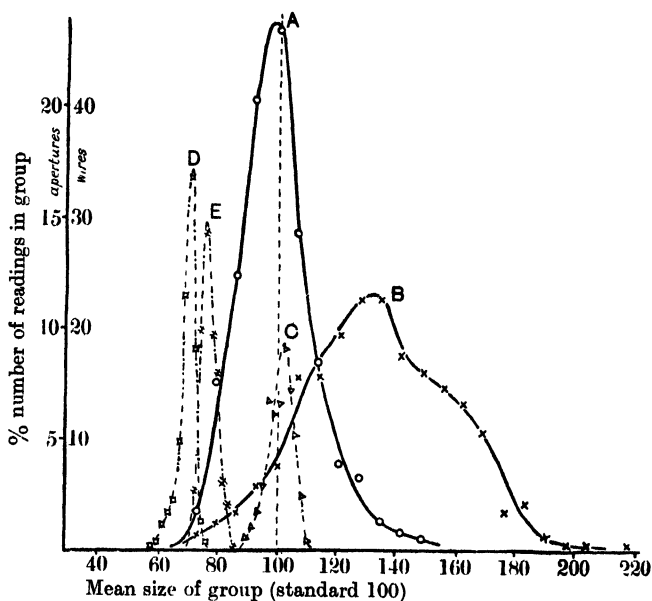


Fig. 2. Double weave.

- Δ , A and C. New—area and wire (half ordinate scale).
- ×, B. Old—area.
- ≠, D and E. Old—wire diam. warp and weft.

The frequency curve for the area of the meshes is shown in *A, Fig. 2*. It is practically symmetrical, except for the greater extension on the right-hand side, due to a few holes of abnormally large size, for which the one strand of wider spacing already mentioned is responsible.

The percentage of readings in excess of 10, 25 and 50 per cent. of the standard values is given in Table I.

The sieve shows a reasonable uniformity in these measurements, and the mean values conform well to standard. The results have been used as a basis of comparison for the worn sieves now to be discussed.

Table I. *New sieve, double weaving.*

	Percentage in excess of		
	10 %	25 %	50 % over standard
Length of side of aperture Direction (<i>A</i>)	13.9 %	3.4 %	nil
Length of side of aperture Direction (<i>B</i>)	6.5 %	nil	nil
Area of aperture	19.6 %	6.7 %	0.5 %

Sieve 2. This was an old used sieve of double weaving. Frequency curves for the width of aperture in both warp and weft directions are shown in Fig. 1, *A* and *D*, for comparison with, and to the same scale as, the corresponding curves *B* and *C* for the new sieve already discussed. Fig. 2 presents a similar comparison of the results for wire diameter and area of aperture.

From an examination of Figs. 1 and 2 it is easy to deduce the manner of the departure from specification brought about by wear.

Both sets of wires in Fig. 2 are distinctly smaller than the standard diameter represented by the vertical line marked at 100, and Set *D* is smaller than Set *E*. This effect is partly due to the stretch of the wires which straightens them—shown in the smaller scatter of the readings—and partly to the effect of wear. This latter is obviously greater in one direction than the other. The readings showed that the narrower set of spaces accompanied the thinner set of wires; in other words, the wires most reduced in diameter were parallel to the direction of greatest stretch, which corresponds with expectation. Also an examination of the photograph (Plate V, *C*) shows that this same set of wires is the looser, and would therefore be likely to suffer most under a rubbing action.

The aperture diameters of this sieve (Fig. 1, *A* and *D*) show wide differences in the two directions. Set *A* has a mean diameter slightly less than the standard, while Set *D* is largely in excess. An initial difference of this kind might be introduced in attaching the sieve to its frame. If the gauze were stretched forcibly in one direction only the wires in that direction would straighten out accompanied by an increase in aperture diameter, while this straightening would cause a contraction in the sieve at right angles by increasing the bends in the other set of wires. As the sieve in question had been given a saucer-shaped form it is more than likely that the initial tension on the wires was uneven. Unevenness of tension in weaving, and also differences in temper or softness of the wire, would tend to be exaggerated under the effect of wear. A second set of readings which confirmed the results just described

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were carried out on another part of the same sieve. The only additional features which emerged were a double peak to one of the curves (an effect which will be referred to later) and a wider spread of the readings in one set of wire diameters. This was found to arise from the bends in the wires in this direction being enhanced, so giving rise to a curved image which gave larger variations in the measurements.

In Table II are given values for enlargement of apertures over standard, which may be compared to the figures in Table I to show the effect of wear.

Table II. *Old sieve, double weaving.*

	Percentage in excess of		
	10 %	25 %	50 % over standard
Length of side of aperture Direction (A)	98.2 %	94.8 %	39.1 %
Length of side of aperture Direction (B)	15.1 %	4.2 %	nil
Area of aperture	85.8 %	69.6 %	35.7 %

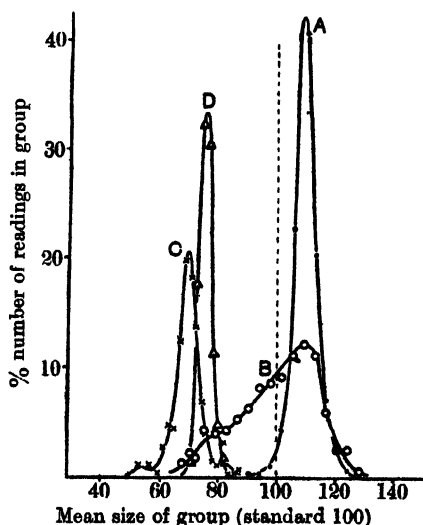
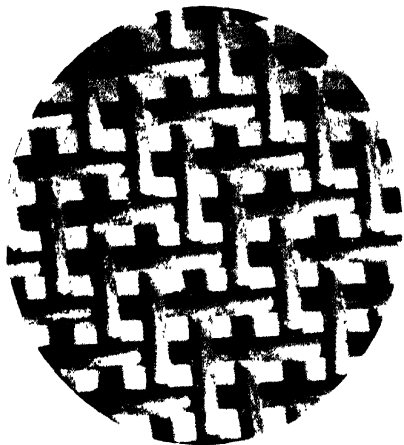


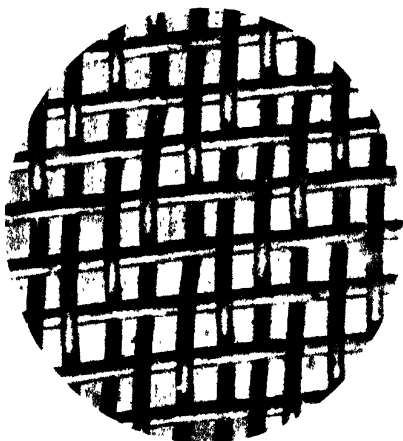
Fig. 3. Single weave.

• o, A and B. Space dimensions. × Δ, C and D. Wire diams.

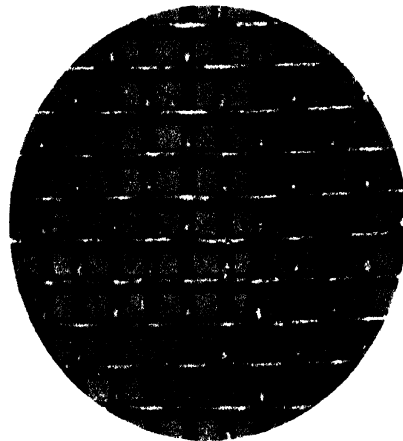
Sieve 3. This was a single weave type, and is illustrated in Plate V, D. The frequency curves for the diameter of the wire in warp and weft directions and the diameter of the holes are given in Fig. 3. The relative displacement of the curves for the wire diameters appears here, as in Sieve 2, but the aperture dimensions are confined within sharper limits. This is especially the case in Set A. The data clearly showed that the



B



C



D

spaces approximate to rectangles with one side (*i.e.* Set *A*) very uniform, and the side at right angles (*i.e.* Set *B*) of varying length. This effect is also shown in Plate V, D, being most clearly seen when the eye is placed near the plane of the paper.

Table III. *Old sieve, single weaving.*

	Percentage in excess of		
	10 %	25 %	50 % over standard
Length of side of aperture Direction (<i>A</i>)	22.7 %	1.6 %	nil
Length of side of aperture Direction (<i>B</i>)	30.7 %	0.7 %	nil
Area of aperture	51.6 %	18.5 %	0.3 %

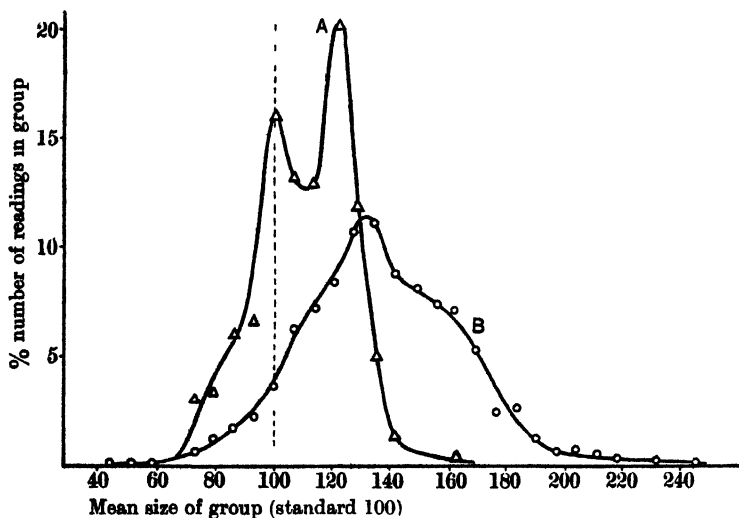


Fig. 4. Areas, *A* single weave, *B* double weave, compared

The frequency curve for area of holes is given in Fig. 4 (*A*) compared with the corresponding curve (*B*) for the double weaving. Comparison of the two curves shows that the single weave sieve is superior to the double weave in its power of maintaining regularity in use. Whereas there are only 18 per cent. of holes in the former that have increased in area by more than 25 per cent., and none of more than 50 per cent. increase, in the double weave 36 per cent. have increased by more than 50 per cent. It is as well to point out however that the double weave sieve had been in use longer and was more worn than the other, and that the comparison assumes that the sieves, when new, both conformed to

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specification as far as the hole areas are concerned. But when allowance is made for these two possible circumstances, the superiority of the single weave sieve is still evident, and is no doubt connected with the fact that there are twice as many interlockings of the warp and weft wires in a given area as compared with the double weaving, and lateral movement of the wires is thus largely prevented. As an offset to this the more angular bends in the wires make them more susceptible to wear and to rupture. In short, a single weave sieve is more reliable but of shorter life, while the double weaving gives a sieve more resiliency, which might lead to its being retained in use long after wear had made it depart widely from

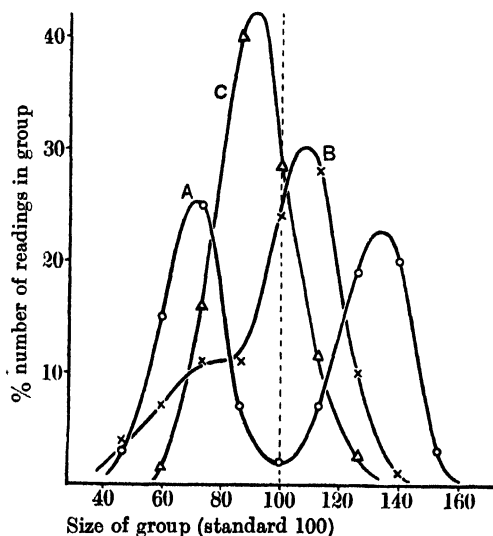


Fig. 5.

o x, A and B. Spaces, parallel to warp (two sets).
 Δ, C. " " " weft (combined).

standard. It will be noticed that the peak of the frequency curve for single weave sieve is bifurcated. Some measurements now to be discussed throw light on this.

The measurements were made on a fourth sieve. In this case two separate patches of the sieve were taken. Frequency curves of the aperture diameters for each patch are shown in Fig. 5. The dimensions of the holes in one direction—the same direction in each patch—are remarkably regular, and in fact, the same curve (C) serves for each set of data. In the other direction one set (A) shows a very marked double peak, but in the other set (B) there is at most only a slight indication of

such a tendency. When the effect occurs, the systematic manner in which the dimensions in question are distributed among the data (being alternately large and small) indicates that it is definite and not due to any chance distribution. The most probable cause appears to be a slight displacement of one of the combs and guides which control the alternate rise and fall of the warp threads in the process of weaving. In this case the spaces between the warp wires of the sieve measured in the weft direction would be alternately wide and narrow, and there would be the minimum number of intermediate sized spaces. The frequency curve would have two peaks corresponding to the preponderance of the wide and narrow spaces. Curves *A* and *B* show that the effect just discussed does not necessarily extend over the whole of the woven material, which indicates that the relative sideways displacement of the guides may not occur over the whole width of the combs.

One general conclusion that emerges from the whole of the above results is that the holes in a new sieve woven according to the I.M.M. specification do not vary largely from the theoretical size, but worn sieves show considerable fluctuations in mesh sizes. The stretching of the wires by use increases the size of some openings and the rubbing action often used to pass material through the sieves produces relative movement of the wires, some of which become crowded together with a consequent reduction in mesh area between them, and a corresponding increase of area in the adjacent portions of the sieve where the wires are wider apart. The stretching of the sieve as a whole and the resulting saucer-like shape is noticeable in the sieves used for mechanical analysis. It becomes of interest therefore to examine the extent to which the holes are enlarged by this stretch. An expression for this is easily deduced.

Assume that the sieve, initially flat, becomes part of the surface of a sphere. The simplest assumption is that the holes are all increased in the ratio $\frac{\text{new area of sieve}}{\text{original area}}$, it being supposed that the effective length of the wire has increased owing to the straightening of the bends between warp and weft, and that no appreciable reduction in wire diameter has occurred. But the more probable manner of the stretching is that, as the sieve gets most rubbing at the centre, the holes in this region are enlarged more than those nearer the periphery.

Before considering these two possible cases it is necessary to obtain some general relations connected with the stretching of the sieve. The inset Fig. 6 shows a piece of a new sieve having the value R for the diameter of wire and of aperture. In the stretched mesh the wire will

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still have the original diameter R but the square hole will have a side of length $R + r$. It will be obvious that the fundamental unit of area in the sieve (*i.e.* that unit which extended in all directions builds up the

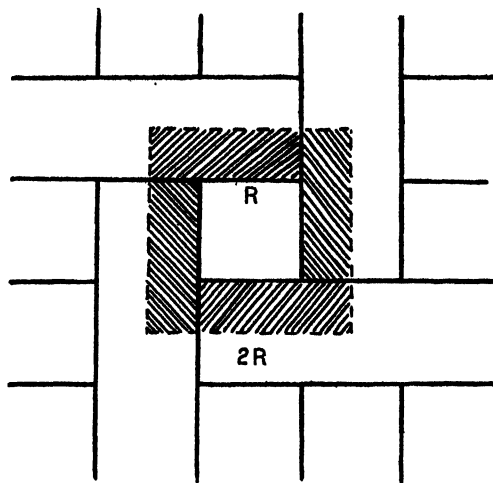


Fig. 6.

complete sieve) is the portion enclosed in the dotted line and shaded. The relations in Table IV follow from the geometry of the figure:

Table IV.

	Area of aperture	Area of wire	Total area
New	R^2	$3R^2$	$4R^2$
Stretched	$(R+r)^2$	$3R^2 + 2Rr$	$4R^2 + 4Rr + r^2$
Difference	$(2Rr + r^2)$	$2Rr$	$4Rr + r^2$

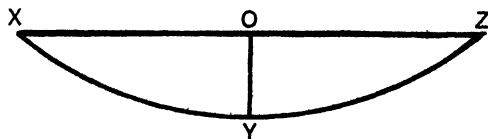


Fig. 7.

The sieve, originally flat, has become a portion of a sphere, and its area has therefore increased (Fig. 7). By a well-known theorem in geometry, the new area is given by

$$\pi(S^2 + A^2) \quad \dots\dots(1),$$

where S = radius of the circular sieve = OZ in Fig. 7, and A = distance centre of sieve has dropped = OY in Fig. 7.

The original area is of course

$$\pi S^2 \quad \dots\dots(2).$$

We can now examine the increase in aperture area for each of the two types of stretching of the sieve.

Case 1. The stretch takes place in the ratio

$$\frac{\text{new area of sieve}}{\text{original area of sieve}} = \frac{S^2 + A^2}{S^2}.$$

From Table IV this ratio is also

$$\frac{4R^2 + 4Rr + r^2}{4R^2}.$$

Hence, equating these two expressions and simplifying,

$$\frac{4Rr + r^2}{4R^2} = \frac{A^2}{S^2} \quad \dots\dots(3).$$

Solving this equation for r , we have

$$r = 2R \left(\frac{\sqrt{A^2 + S^2}}{S} - 1 \right) \quad \dots\dots(4).$$

This equation gives the increase in length of the side of the hole (r) in terms of the original length R , the radius of the sieve S , and the distance A , through which the centre of the sieve has dropped. We are now able to calculate the percentage increase in area of the holes. This increase is from Table IV

$$\frac{2Rr + r^2}{R^2} \times 100 \quad \dots\dots(5).$$

Substituting in this expression the value of r from (4), and simplifying, we obtain

$$\frac{400}{S^2} \{A^2 + S^2 - S\sqrt{A^2 + S^2}\} \quad \dots\dots(6).$$

This expression gives the percentage increase in the area of the holes, in terms of the ratio A/S .

The following table gives the percentage increase of area for various values of A/S .

Table V.

Value of ratio A/S	Per cent. increase in area of sieve holes
$\frac{1}{4}$	12.4 %
$\frac{1}{3}$	8.0
$\frac{1}{2}$	4.1
$\frac{1}{\sqrt{2}}$	2.0
$\frac{1}{\sqrt{3}}$	0.5

It will be seen from the table, that even in the case where $A/S = \frac{1}{4}$ (*i.e.* the centre of the sieve has sunk a distance equal to $\frac{1}{4}$ th of the sieve diameter) the percentage increase in size of hole diameter is not more

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than 12 per cent. A value of $\frac{1}{4}$ for A/S represents a considerable stretch in the sieve, and if the increase in hole diameter were related to increase of sieve area in the manner assumed above, it could be safely stated that no serious error would be caused by stretch during wear, until this reached considerable dimensions.

Case 2. It is however improbable that the above assumption represents the facts, at any rate in sieves used for mechanical analysis. These get most rubbing over the central portion, and it is reasonable to assume that the degree to which the sieve is stretched increases from the periphery to the centre.

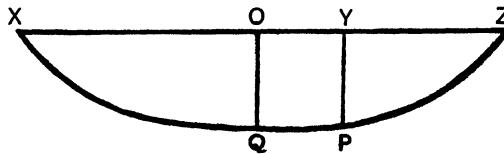


Fig. 8.

Assume that this increase in area of a sieve unit P (Fig. 8), originally at Y , is proportional to the distance YZ , i.e. is equal to

$$K(S - y) \quad \text{.....(7),}$$

where

$$S = OZ = \text{radius of sieve,}$$

$$y = OY,$$

$$K = \text{constant.}$$

Now the original area of an annular ring of small width passing through Y is

$$2\pi y \, dy,$$

and hence its increase in area is by (7)

$$2\pi K y (S - y) \, dy;$$

\therefore the total increase in area is

$$2\pi K \int_0^S y(S - y) \, dy = \frac{\pi}{3} K S^3 \quad \text{.....(8).}$$

But as the stretched sieve is assumed to be part of a sphere, we have already seen that the increase of area is

$$\pi A^2 \quad \text{.....(9),}$$

where

$$A = \text{distance } OQ.$$

Hence equating (8) and (9) we have

$$K = \frac{3A^2}{S^3} \quad \text{.....(10).}$$

Hence expression (7) for the increase in area of a unit mesh becomes

$$\frac{3A^2}{S^3}(S-y) \quad \text{.....(11).}$$

Now from Table IV the area of unit mesh is $4R^2$, therefore at the point P (Fig. 8) its increase is, from (11),

$$4R^2 \frac{3A^2}{S^3}(S-y) \quad \text{.....(12).}$$

But from Table IV its increase is also

$$(4Rr + r^2) \quad \text{.....(13).}$$

Equating (12) and (13) and solving for r , we have

$$r = 2R \left\{ \sqrt{\left(\frac{3A^2(S-y)}{S^3} + 1 \right)} - 1 \right\} \quad \text{.....(14).}$$

This equation gives the increase in length of the side of any hole in terms of its original length (R), the radius of the sieve (S), the distance the centre point of the sieve has sunk (A), and the original distance y of the hole from the centre of the sieve.

The percentage increase in area of the hole itself is, from Table IV,

$$\frac{2Rr + r^2}{R^2} \times 100.$$

Substituting in this expression the value for r given by (14) and simplifying, we have for the percentage increase of hole area

$$400 \left[\frac{3A^2(S-y)}{S^3} + 1 - \sqrt{\left(\frac{3A^2(S-y)}{S^3} + 1 \right)} \right].$$

Hence by giving various values in terms of S the sieve radius to A and y , we can find the percentage increase of the area of the holes, at any point on the sieve. These values are given in Table VI for different values of A . Values for y have been taken in steps of one-tenth the sieve radius S .

Table VI.

Value of A	$S/4$	$S/5$	$S/7$	$S/10$
Value of y in terms of S	Percentage increase of area of the holes			
0	39.2	24.7	12.4	6.0
.1	35.6	22.2	11.2	5.4
.2	31.6	19.6	9.9	4.8
.3	27.6	17.1	8.7	4.2
.4	25.6	14.6	7.4	3.6
.5	19.2	12.2	6.2	3.0
.6	15.2	9.7	4.9	2.4
.7	11.2	7.7	3.7	1.8
.8	7.3	4.8	2.4	1.2
.9	3.7	2.4	1.2	0.6
1.0	0	0	0	0

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The variations of hole area in this table are more serious than those calculated on the first assumption. For instance, in the case where the sieve centre has sunk a distance of $1/14$ th the sieve diameter ($A = S/7$), the central holes have increased in area by 12.4 per cent. Again, a central patch of the sieve initially of radius equal to 0.3 that of the sieve itself, and therefore nearly $1/10$ th of the original sieve area, has its holes increased in size by 8.7 per cent. or more. These calculated increases give an idea of the change to be expected with stretch of a sieve, when the meshes maintain their relative positions. In practice, especially if the sieve is rubbed in any way during use, the loosening of the wires causes

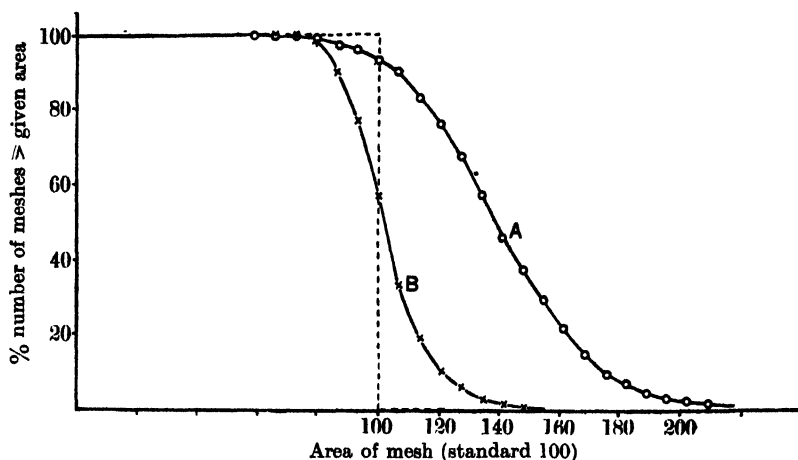


Fig. 9.

o A, Old sieve. x B, New sieve. Ideal sieve.

them to move relatively to one another and hence spaces much larger than those calculated occur, together with those of considerably decreased area, where the wires have been crowded together. The degree to which this occurs is shown in the data obtained for worn sieves. A comparison of an ideal, a new, and a worn sieve is conveniently expressed in the form of Fig. 9 which shows the chance any particle of a given cross-sectional area has of passing through the sieves. The curves are constructed from the frequency data already discussed, by plotting as ordinates the total number of holes of area equal to or greater than the area indicated by the abscissa. No account is taken of the fact that the shape of cross-section of the particles will not coincide exactly with that of the holes, and it is assumed that the sieve is shaken long enough for all particles, whose size allows, to pass through.

In actual practice the shape of the particle, the time of shaking and the method of shaking will all operate in determining the size of the material passing through or held by the sieve. A test was made to see whether the sieves examined above allowed different percentages of material to pass through. Soil particles were used, a mixture of equal parts coarse sand and fine silt fractions being made up. The results were as follows:

New double weave sieve passed 0.4 per cent. of that material which it should have held.

Old double weave sieve passed 1.6 per cent. of that material which it should have held.

Old single weave sieve passed 0.9 per cent. of that material which it should have held.

The differences are small but are in the direction to be expected from the measurements made on the sieves. Soil is a heterogeneous mixture as far as shape and size of particles are concerned, and in the samples made up there was a comparatively small percentage of particles over the critical range of diameters. In the case of commercial products there is no doubt that much bigger differences would be obtained, especially in those cases where it was important for technical reasons that the particles passing a given sieve should have only a narrow range of size.

SUMMARY.

A series of measurements of wire diameter, length of side, and area of holes, has been made on new and used sieves, all of which were originally of the "100 mesh" size, *i.e.* the square holes were supposed to be .01" in length of side and the wire to be .01" in diameter. The measurements have been expressed as frequency curves.

In the case of unused sieves woven to the I.M.M. specification, the sieve on the whole compared well with the specification, but in used sieves the variations were much greater. The divergence from specification in the new and old sieves is shown by Tables I and II respectively.

In one sieve (No. 2) the holes elongated more in one direction than the other. In fact in one direction the alteration which has taken place is a contraction rather than a stretch. This effect was probably connected with the manner in which the sieve was attached to its metal framework, and also to difference in tempering of the wires and the tension in weaving.

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A number of the frequency curves showed double peaks, and the actual observations showed that there was a systematic distribution of values corresponding to these two peaks. It is probable that some of the guides in one of the combs through which the warp wires are led during the weaving were displaced sideways, thus giving alternate strands of wire and narrow holes. This was particularly the case in the single weave.

The two systems of weaving—double and single (see Plate V, figs. A and D respectively)—were compared. The latter design appears preferable for maintaining uniformity of hole dimensions in use, since the wires grip one another more tightly and more often, although it is intrinsically neither as strong nor as durable as the double weaving.

A calculation is made to show the effect that stretch of the wires in use has on the dimensions of the holes, it being assumed that the warp and weft wires maintain their relative positions and do not slip over one another. This latter assumption is scarcely true as the actual measurements and photographs indicate.

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WHEAT OFFALS: THEIR GRADING, COMPOSITION AND DIGESTIBILITY.

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1. DEFINITION OF THE TERM "MILLERS' OFFALS."

In 1913 the National Association of Millers was invited by the Board of Agriculture to formulate a definition of the term "Millers' Offals." After some discussion the Association forwarded the following resolution: "That millers' offals, or wheaten offals sold as such, are the products of wheat and of the vegetable substances extracted from the wheats of commerce in the process of cleaning; but the proportion of such extraneous matter shall not exceed the percentage found in the wheats imported into the United Kingdom."

In practice the various classes of wheat offals are extracted from that portion of the milled wheat kernels which does not pass through the silk sieves used for separating out the flour (Nos. 10 to 14 with 106 to 140 meshes per linear inch respectively).

From the foregoing definition it follows that screenings extracted from wheats can legitimately be ground separately and mixed with the offals obtained from the cleaned wheat. The percentage extracted is usually about 3 per cent. They consist for the most part of very small berries or broken and shrivelled wheat, together with oats, barley and other seeds. In the usual practice the screenings are not separated into their component parts, but are ground together. From this mixed

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product it is possible to extract a substantial proportion as fine as flour; indeed, much of it is wheaten flour arising from the broken and shrivelled wheat grains of the screenings. This material constitutes the principal source of the floury particles which occur in the finer grades of offals. Relatively little of the ground screenings finds its way into broad bran.

2. COMPOSITION AND CLASSIFICATION OF WHEAT OFFALS (Wood and Adie, 1917).

An interesting attempt was made by Wood and Adie⁽¹⁾ in 1917 to place the classification of wheat offals on a definite and uniform basis. They pointed out that considerable confusion had arisen in attempting to assign an average composition to wheat offals described by local names. It frequently happened that the same name was employed in different localities to designate grades of offals which differed widely in regard to both size of particles and chemical composition. The main confusion was due to variation in milling practice in different districts and to the fact that whilst the larger mills separated their offals into four grades, many of the smaller mills were satisfied with a much less complicated separation.

With a view to finding a way out of this difficulty Wood and Adie made a systematic investigation of a large number of representative samples of offals. The latter were collected before the issue of the first war-time Milling Order and represented therefore normal pre-war offals. The results of sifting showed that in the mills where the offals were most completely separated, the separation fell approximately into four grades:

Grade 1. Bran, which does not pass through wire sieve No. 16.

Grade 2. Pollards, which does not pass through wire sieve No. 24 but passes through wire sieve No. 16.

Grade 3. Coarse middlings, which does not pass through silk sieve No. 3 but passes through wire sieve No. 24.

Grade 4. Fine middlings, which does not pass through the silks ranging from Nos. 10 to 14 used for sifting out flour, but passes through silk sieve No. 3 (56 meshes per linear inch).

The samples from many mills, however, where the separations were not so thorough, did not fall entirely in any one of these grades. Some of them were mixtures of two grades, whilst in others the samples included three grades.

The investigation of the size of the particles indicated therefore that, exclusive of the extreme fractions flour and bran, offals could be divided into three "pure grades" and three "mixed grades." Chemical analysis

demonstrated further that this classification possessed a definite value, since there was practically no overlapping in the composition of the pure grades. The average results of the analyses, calculated to the dry matter basis, are given in the following table.

		Protein %	Fat %	Carbohydrates %	Fibre %	Ash %
<i>Grade 1.</i>	Bran	15.57	4.53	61.40	12.25	6.25
" 2.	Pollards	16.60	5.49	64.03	8.88	5.00
" 3.	Coarse middlings	18.98	5.81	64.96	6.11	4.14
" 4.	Fine middlings	18.05	3.94	73.11	2.13	2.77

The characteristic of the fine middlings is a very high content of carbohydrates. Coarse middlings contain much more fibre than the fine middlings. The fibre content also serves to mark off pollards from coarse middlings and bran. The percentages of carbohydrate decrease and those of fibre and ash increase continuously as the size of the particles becomes larger. In the case of protein and fat, however, the percentages are highest in Grade 3 (coarse middlings) and decrease as the particles become either finer or coarser than this grade. This is probably a consequence of the concentration of the germ in the coarse middlings.

As a result of their enquiry, Wood and Adie concluded that the indefinite grading in vogue at the time and the great variation in local names made it impossible to assign a standard composition and a definite feeding value to any kind of offal except bran. They rightly urged that this must prove a considerable handicap against the sale of offals and suggested that millers should adopt a uniform system of grading and naming their offals. An alternative proposal was put forward whereby local names could be retained, provided the offals were sold with a simple designation indicating the size of particle. In conclusion, they pointed out the desirability of carrying out digestibility trials on typical samples of each grade, with a view to establishing the feeding value of each grade with greater certainty.

3. EFFECT OF WAR-TIME CONTROL ON GRADING AND COMPOSITION OF WHEAT OFFALS.

The control exercised over the milling industry during the later years of the war has resulted in a definite modification in the division and naming of offals. The most striking effect concerns the grade known as pollards, which seems to have disappeared almost entirely from the market.

A very comprehensive investigation into the types of wheat offals being manufactured in this country since control of the industry was

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discontinued has been carried out by Dr A. E. Humphries¹, of Coxes Lock Mill, Weybridge. In all 83 samples of offals were collected from 31 firms trading in all parts of England and Wales. The firms in question were asked to send a sample of every grade sold in ordinary trading. No sample was received which bore the designation pollards or corresponded with the grade of pollards tested by Wood and Adie in 1917. Writing in the March of 1923 Dr Humphries says: "I see, however, from our trade papers that the term pollards is still used in a very few districts, and it is applied to some of the offals imported from Argentine. Nevertheless, I think it can be said that control destroyed the grade and that it has not been resuscitated."

Broad or flaked bran is now produced in large quantities; this extraction involves a division of straight run bran, and as a consequence the grades of bran sold as medium bran, fine bran and No. 2 bran arise. It is probable that some of the product known formerly as fine pollards now gets into the finer brans and some, after regrinding, into the middlings.

By means of sifting the 83 samples of offals were divided into seven main groups. The sifting data are given in the following table:

Group	Size of particle		Number of samples falling into group
A	At least 75 %	over No. 10 wire sieve	13
B	" 75 %	" " "	18
C	" 75 %	" " "	14
D	" 50 %	" " "	5
E	" 50 %	" " and }	28
F	" 25 %	through 56 "	
G	" 50 %	" 56 "	2
	" 75 %	" 56 "	3

From the above data it was concluded that the groups A, B and C were subdivisions of what has hitherto been regarded as one grade of offal, namely bran. Subsequent chemical analysis proved the correctness of this conclusion. The finer grade of bran under group C contains a proportion of the material known as pollards, but the results of chemical analysis of this group, together with the fact that the samples only pass in part through the No. 16 wire sieve, establish the offals in group C as brans.

An examination of the sifting returns of the five samples of offals in

¹ The thanks of the Institute are due to Dr Humphries for his valuable co-operation in this investigation. Dr Humphries was not only responsible for the important work of collecting and sifting the numerous samples of offals, but has further supplied the writer with a mass of interesting information which has been made use of in compiling the present account.

group D revealed the fact that they cannot be regarded as constituting a typical grade of offals, but arise merely as an overflow from recognised grades. In an arbitrary method of grading, such samples get just outside the two recognised grades of bran and middlings. Two of the five samples on the one hand closely resembled bran, whilst, on the other hand, another two gave sifting results indicating resemblance to middlings. The fifth sample appeared to be simply bran with a very large proportion of the broad flakes removed.

From the standpoint of feeding experiments on typical grades of offals the samples in group D may be ignored, since so little of this quality is made in the United Kingdom.

The E group of offals may be taken as representing the average middlings now being produced in this country. The difference between the E and F groups arises from the presence of a large proportion of finer particles in F. Since, however, only two of the 83 samples investigated came into group F, it is feasible to ignore this group altogether when selecting typical samples for digestibility experiments.

The group G offals approximate to the old fine middlings and possess a special interest. They represent an extremely small fraction of the offals made in the kingdom. Two of the samples came from South Wales, whilst the remaining sample came from South Devon. In South Wales there is a great demand for high grade flours and a correspondingly poor demand for the lower grades. In practice this results in a low extraction of flour from the wheats and the appearance of much low grade flour in the offals. 48 per cent. of these fine offals will pass through the No. 10 silk sieve; in other words, about half of these offals consists of low grade flour, and indeed such offals might be used in the making of dog biscuits. Although so little of these fine offals find their way on to the market, it was considered of special interest to determine by animal experiment their digestibility and food value, with a view to encouraging their production on a larger scale.

In the investigation of the samples of offals collected by Dr Humphries it was manifestly impossible to submit them individually to chemical analysis; nor, indeed, was such a course really essential. Instead of this seven composite samples representative of the various groups were made up, each one containing a correct proportion of the original samples in the groups. The composite samples were then submitted to analysis¹, with the following results (calculated to dry matter basis):

¹ The writer is indebted to A. J. Codling, Esq., for the results of the analysis of the composite samples.

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Group	Ether extract %	Crude protein %	N-free extractives %	Crude fibre %	Ash %
A	5.19	16.32	60.86	11.01	6.62
B	5.30	16.38	60.84	10.87	6.61
C	5.41	16.35	60.90	10.85	6.49
D	5.99	17.75	61.41	9.23	5.62
E	5.68	18.21	65.61	6.28	4.22
F	5.60	17.24	66.44	6.48	4.24
G	4.62	19.52	70.56	2.48	2.82

The results of the analysis amply confirm the assumption that no substantial difference exists between the groups A, B and C, and that they can be regarded as grades of bran. The figures further bring out the resemblance between the groups E and F, and also demonstrate the character of D as being intermediate between bran and middlings. The results for group G offals are very striking and lead one to anticipate a high feeding value for this grade.

On the basis of the above results, it was decided that present-day offals fell into three grades, namely, Brans (A, B and C), Middlings (E and F) and Fine Middlings (G). It is of interest therefore to compare the analytical results for these three typical grades.

Grade	Ether extract %	Crude protein %	N-free extractives %	Crude fibre %	Ash %
B. Bran ...	5.30	16.38	60.84	10.87	6.61
E. Middlings ...	5.68	18.21	65.61	6.28	4.22
G. Fine middlings	4.62	19.52	70.56	2.48	2.82

It will readily be discovered from the above figures that the classification based on size of particles separates the offals into grades which possess very sharply differentiated chemical characters. The fine middlings show a high content of carbohydrates, the percentage of the latter decreasing continuously as the size of the particles increases. The crude fibre content also displays a continuous variation in the reverse sense, being very low in the fine middlings and increasing continuously as the size of the particles in the offals increases. A precisely similar variation characterises the ash content. The amount of protein increases continuously from bran to fine middlings, although the amount of variation is not so considerable as in the cases of the other ingredients of the offals. In respect of the fat constituent the percentage is highest in the middlings and decreases as the particles become either finer or coarser than in this grade. It will finally be noted that the above findings are in substantial accord with those obtained by Wood and Adie in their work on the composition of pre-control wheaten offals.

Since wheat offals, as made at the present time, had thus satisfactorily been divided into three main typical groups, it was now essential to carry out digestion trials on samples of these grades. It was hoped in this way to correlate size of particles not only with chemical composition but also with feeding value and thus to encourage a universal production of wheat offals on a simple and uniform basis.

It might be urged, however, that the vast amount of time and labour involved in such determinations might to a large extent be wasted, in view of the circumstance that the character of wheat offals sold on the market is in some measure subject to the economic conditions obtaining at the time. In this connection, however, Dr Humphries writes: "I think the grading of offals is now as settled as it ever will be; the material changes were made during Control and were due to the conditions then prevailing. The industry has now been out of control for some considerable time, and I think we may accept the present position as to the grading of offals as one that is likely substantially to continue so long as wheat and offals are of the same relative values."

4. DIGESTIBILITY AND RELATIVE FOOD VALUES OF BRAN AND BROAD BRAN.

Broad bran is ordinarily obtained by sifting out the largest flakes from straight run bran, the remainder constituting medium bran or fine bran. It is sometimes the practice to pass bran between smooth rollers. In this way "curly" bran is flattened, and the effect may be intensified if the bran is steamed immediately prior to rolling.

The broad bran tested in the present trials had resulted from the simple sifting of straight run bran.

A considerable number of feeders prefer the larger flakes and consequently the miller can command a better price for the broad bran. In the latter practically all the dusty material has been removed. It is claimed that broad bran makes a better mash for stock and a more bulky feed when soaked. Horses are said to prefer broad bran and to do better on it, although its analysis does not differ materially from that of ordinary bran. The difference in price is from 15 to 35 shillings per ton in favour of broad bran as compared with medium or fine bran.

The object of the digestion trials with the two kinds of bran was to ascertain whether, from the standpoint of food value, there existed sufficient justification for the higher cost of broad bran and for the extra labour entailed in effecting this division of straight run bran.

The experimental technique employed in the trials was similar to that described in previous communications(2). The experiment was

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divided into three separate periods, the nature of the foodstuffs being tested necessitating the inclusion of a basal period on a diet consisting of a mixture of chaffed meadow hay and linseed cake. The bran was fed dry.

The measurements were made in duplicate on wethered sheep, which were equipped with the harness designed by Halnan and were kept in the usual digestion crates. The periods were of a duration of three weeks, made up of a week's preliminary feeding followed by a fortnight's collection and analytical period. At the beginning and end of each period, the sheep were weighed. The nitrogen balances were also determined.

The daily rations for the whole period were weighed out into paper bags at the beginning of each separate period, and the samples for moisture determinations and complete analysis were taken at the same time. Bi-weekly composites of urine and faeces were made up for the determination of nitrogen content. The moisture content of the faeces was found by drying down aliquot portions of the composite samples at 60–65° C. in an air oven, the residues after drying being preserved for making up the period composite samples. The latter were finely ground up, air dried and submitted to analysis.

The care of the sheep was again in the experienced hands of Mr F. J. Aylett, who also rendered valuable assistance in connection with the analytical work.

Table I. *Details of rations.*

	Daily ration
Basal period ...	500 gm. meadow hay 100 „ linseed cake
Ordinary bran period	500 „ meadow hay 100 „ linseed cake 600 „ ordinary bran
Broad bran period ...	500 „ meadow hay 100 „ linseed cake 600 „ broad bran

Table II. *Composition of foodstuffs* (calculated to dry matter basis).

	Meadow hay	Linseed cake	Ordinary bran	Broad bran
	%	%	%	%
Crude protein ...	10.58	32.90	17.32	16.86
Ether extract ...	3.43	7.17	4.44	4.59
N-free extractives	50.15	42.46	60.71	59.83
Crude fibre ...	28.66	10.09	10.87	11.86
Ash ...	7.18	7.38	6.66	6.86
				%
Mean dry matter in hay	throughout trial			86.83
„ „ linseed cake				87.50
„ „ ordinary bran				87.00
„ „ broad bran				86.00

It will be noted that the figures for the two brans are very similar, the ordinary bran being slightly richer in crude protein and carbohydrates but slightly poorer in fibre. This difference is probably occasioned by the presence of fine particles in the ordinary bran. Both brans are somewhat less rich in fat than the composite bran samples prepared by Dr Humphries and discussed earlier in this communication.

Table III. *Average daily weight and composition of faeces.*

1. Basal period.

	Sheep I	Sheep II
Mean weight of fresh faeces daily	432.0 gm.	424.0 gm.
" " dry matter "	197.1 "	188.8 "

Composition of dry matter.

	Sheep I %	Sheep II %
Crude protein*	14.11	13.89
Ether extract	4.14	4.19
N-free extractives	44.92	44.56
Crude fibre	24.31	23.91
Ash	12.52	13.45
Pepsin-HCl insoluble protein	6.27	6.44
* Nitrogen as determined on <i>fresh</i> faeces	1.014	0.999

2. Ordinary bran period.

	Sheep I	Sheep II
Mean weight of fresh faeces daily	1409.0 gm.	1653.0 gm.
" " dry matter "	408.2 "	426.8 "

Composition of dry matter.

	Sheep I %	Sheep II %
Crude protein*	12.31	11.62
Ether extract	8.97	9.73
N-free extractives	43.13	42.58
Crude fibre	21.60	21.71
Ash	13.99	14.36
Pepsin-HCl insoluble protein	5.94	5.55
* Nitrogen as determined on <i>fresh</i> faeces	0.587	0.506

3. Broad bran period.

	Sheep I	Sheep II
Mean weight of fresh faeces daily	1420.0 gm.	1679.0 gm.
" " dry matter "	392.4 "	428.1 "

Composition of dry matter.

	Sheep I %	Sheep II %
Crude protein*	12.00	11.09
Ether extract	7.22	9.37
N-free extractives	44.14	43.71
Crude fibre	22.37	21.94
Ash	14.27	13.89
Pepsin-HCl insoluble protein	5.55	5.41
* Nitrogen as determined on <i>fresh</i> faeces	0.528	0.477

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Table IV. *Digestibility of basal ration.*

Daily ration: 500 gm. meadow hay.
100 gm. linseed cake.

Sheep I.

			Total dry matter gm.	Organic matter gm.	Crude protein gm.	Ether extract gm.	N-free extract- tives gm.	Crude fibre gm.	Ash gm.
Consumed:									
Meadow hay	...	...	434.20	403.02	45.94	14.89	217.75	124.44	31.18
Linseed cake	...	...	87.50	81.04	28.79	6.27	37.15	8.83	6.46
Total	...	...	521.70	484.06	74.73	21.16	254.90	133.27	37.64
Voided	...	...	197.10	172.42	27.38*	8.16	88.54	47.91	24.68
Digested	...	...	324.60	311.64	47.35	13.00	166.36	85.36	12.96
Digestion coefficients, %	...	...	62.22	64.38	63.36	61.44	65.26	64.05	34.43

Sheep II.

Consumed (as above)	...	...	521.70	484.06	74.73	21.16	254.90	133.27	37.64
Voided	...	...	188.80	163.40	26.50*	7.91	84.13	45.14	25.40
Digested	...	...	332.90	320.66	48.23	13.25	170.77	88.13	12.24
Digestion coefficients, %	...	...	63.81	66.24	64.54	62.61	66.99	66.13	32.52
Mean digestion coefficients, %	...	...	63.00	65.30	64.00	62.00	66.10	65.10	33.50

* Calculated on nitrogen of *fresh faeces*.

Protein digestibility corrected for metabolic nitrogen.

	Sheep I	Sheep II
Protein consumed, gm.	...	...
Pepsin-HCl insoluble protein voided, gm.	74.73	74.73
Protein digested, gm.	12.36	12.16
Corrected digestion coefficients, %	62.37	62.57
Mean corrected digestion coefficient, %	83.46	83.73
	83.60	

The results for both sheep display very satisfactory agreement, Sheep II showing on the whole a somewhat more efficient utilisation of the nutrients of the ration than Sheep I. The digestion coefficient of the fat ingredient is lower than was anticipated, since an exactly similar trial carried out with the same sheep about eighteen months previously gave a digestion coefficient of 72 per cent. for the fat. Extended reference will be made later to peculiar fat digestibility values obtained during the course of this work. At this stage, however, it appears possible that the efficiency with which the sheep utilise food fat has undergone diminution with increasing age.

The results obtained with both sheep in the ordinary bran period (see Table V) are very noteworthy, especially that for the utilisation of bran fat. Comment on this remarkable feature will be withheld until the results of the broad bran period have been given.

Table V. *Digestibility of ordinary bran.*

Daily ration: 500 gm. meadow hay.
100 gm. linseed cake.
600 gm. ordinary bran.

Sheep I.

		Total dry matter gm.	Organic matter gm.	Crude protein gm.	Ether extract gm.	N-free extrac- tives gm.	Crude fibre gm.	Ash gm.
Consumed:								
Meadow hay	...	434.20	403.02	45.94	14.89	217.75	124.44	31.18
Linseed cake	...	87.50	81.04	28.79	6.27	37.15	8.83	6.46
Ordinary bran	...	522.00	487.24	90.41	23.18	316.91	56.74	34.76
Total	...	1043.70	971.30	165.14	44.34	571.81	190.01	72.40
Voided (total)	...	408.20	351.10	51.69*	36.62	176.06	88.17	57.10
From basal ration	...	197.10	172.42	27.38	8.16	88.54	47.91	24.68
From ordinary bran	...	211.10	178.68	24.31	28.46	87.52	40.26	32.42
Digested from bran...	...	310.90	308.56	66.10	—	229.39	16.48	2.34
Digestion coefficients, %	...	59.56	63.33	73.11	—	72.39	29.04	6.73

Sheep II.

Consumed (as above)	...	1043.70	971.30	165.14	44.34	571.81	190.01	72.40
Voided (total)	...	426.80	365.51	52.25*	41.53	181.73	92.65	61.29
From basal ration	...	188.80	163.40	26.50	7.91	84.13	45.14	25.40
From ordinary bran	...	238.00	202.11	25.75	33.62	97.60	47.51	35.89
Digested from bran...	...	284.00	285.13	64.66	—	219.31	9.23	—
Digestion coefficients, %	...	54.41	58.52	71.52	—	69.20	16.27	—
Mean digestion coefficients, %	...	57.00	60.90	72.30	—	70.80	22.70	—

* Calculated on nitrogen of *fresh* faeces.

Protein digestibility corrected for metabolic nitrogen.

	Sheep I	Sheep II
Consumed, gm.	90.41	90.41
Total pepsin-HCl insoluble protein voided, gm.	24.25	23.69
From basal ration, gm.	12.36	12.16
From bran, gm.	11.89	11.53
Protein digested from bran, gm.	78.52	78.88
Corrected digestion coefficients, %	86.84	87.25
Mean corrected digestion coefficient, %	87.00	

Comments on Tables V and VI.

The agreement obtained between the two sheep in both the ordinary bran and broad bran periods is not so good as that which characterised the basal period. The lack of harmony, however, is not so pronounced as would appear from the bran digestion coefficients, since if the digestion coefficients for the constituents of the *whole* rations fed in the bran periods be calculated, then the agreement between the results for the sheep becomes more satisfactory (see Table VII).

With the exception of the figures for ash and fat, the latter of which will later be shown to be abnormal, the harmony in the results for the sheep in both trials is reasonably good. The somewhat wider discrepancies

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Table VI. *Digestibility of broad bran.*

Daily ration: 500 gm. meadow hay.
100 gm. linseed cake.
600 gm. broad bran.

Sheep I.

		Total dry matter gm.	Organic matter gm.	Crude protein gm.	Ether extract gm.	N-free extrac- tives gm.	Crude fibre gm.	Ash gm.
Consumed:								
Meadow hay	...	434.20	403.02	45.94	14.89	217.75	124.44	31.18
Linseed cake	...	87.50	81.04	28.79	6.27	37.15	8.83	6.46
Broad bran	...	516.00	480.60	87.00	23.68	308.72	61.20	35.40
Total	...	1037.70	964.66	161.73	44.84	563.62	194.47	73.04
Voided (total)	...	392.40	336.40	46.88*	28.32	173.21	87.78	56.00
From basal ration	...	197.10	172.42	27.38	8.16	88.54	47.91	24.68
From broad bran	...	195.30	163.98	19.50	20.16	84.67	39.87	31.32
Digested from bran...	...	320.70	316.62	67.50	3.52	224.05	21.33	4.08
Digestion coefficients, %	...	62.15	65.88	77.58	14.86	72.58	34.85	11.53

Sheep II.

Consumed (as above)	...	1037.70	964.66	161.73	44.84	563.62	194.47	73.04
Voided (total)	...	428.10	368.64	50.00*	40.11	187.12	93.93	59.46
From basal ration	...	188.80	163.40	26.50	7.91	84.13	45.14	25.40
From broad bran	...	239.30	205.24	23.50	32.20	102.99	48.79	34.06
Digested from bran...	...	276.70	275.36	63.50	—	205.73	12.41	1.34
Digestion coefficients, %	...	53.63	57.29	73.00	—	66.63	20.28	3.79
Mean digestion coefficients, %	...	57.90	61.60	75.30	—	69.60	27.60	7.70

* Calculated on nitrogen of *fresh* faeces.

Protein digestibility corrected for metabolic nitrogen.

	Sheep I	Sheep II
Consumed, gm.	87.00	87.00
Total pepsin-HCl insoluble protein voided, gm.	21.78	23.16
From basal ration, gm.	12.36	12.16
From bran, gm.	9.42	11.00
Digested from bran, gm.	77.58	76.00
Corrected digestion coefficients, %	89.17	87.36
Mean corrected digestion coefficient, %	88.30	

Table VII. *Digestibility of complete rations fed in ordinary bran and broad bran periods.*

	Ordinary bran period		Broad bran period	
	Sheep I %	Sheep II %	Sheep I %	Sheep II %
Dry matter	60.88	59.11	62.18	58.75
Organic matter	63.85	62.37	65.13	61.79
Crude protein	68.70	68.36	71.01	69.09
Ether extract	17.41	6.34	36.84	10.55
N-free extractives	69.21	68.22	69.27	66.80
Crude fibre	53.59	51.24	54.86	51.70
Ash	21.13	15.35	23.33	18.59

which reveal themselves in calculating the digestion coefficients of the bran constituents arise from the fact that in the basal period Sheep II digested its food slightly more thoroughly than did Sheep I, whereas in the bran periods Sheep I utilised its ration more efficiently than did Sheep II. In calculating the digestion coefficients of the brans, therefore, the two sets of divergencies did not cancel each other, as is usually the case, but operated additively. It is instructive to note in Table VII that good agreement exists in the main between the results from Sheep I in the ordinary bran and broad bran periods. The same remark also applies to the results from Sheep II and leads to the conclusion that very little difference exists between the food values of the two types of bran. That this is actually the case will be shown more clearly at a later stage.

The outstanding features of Tables V and VI are revealed in a study of the figures obtained for the utilisation of the fat constituent of the brans. The results for both sheep in the ordinary bran period gave a negative digestibility for bran fat; that is to say, they were excreting more ether soluble material in the faeces, after making allowance for that arising from the basal portion of the ration, than was contained in the bran itself. In the broad bran period, a similar result was given by Sheep II, whilst for Sheep I the abnormally low digestion coefficient of 14.86 per cent. was obtained for the bran fat.

These results had every appearance of abnormality, since it is only usual to encounter such negative digestibilities where a foodstuff extremely poor in fat is tested. Consequently, before proceeding to investigate the meaning of this abnormality, a further test with a new sample of ordinary bran was carried out with the same sheep. Attempts to carry out a short period trial with bran alone failed, owing to the sheep becoming scoured. The new trial lasted ten days and attention was solely directed to the assimilation of the bran fat. The results were as follows:

Table VIII.

Daily ration: 500 gm. meadow hay + 100 gm. linseed cake + 600 gm. ordinary bran.

Amount of ether extract in hay			per day - 13.49 gm.	
" " linseed cake			" - 10.52 "	
" " ordinary bran			" - 33.66 "	
Total amount of ether extract consumed			" = 57.67 "	
			Sheep I	Sheep II
Ether extract voided	per day	... ..	27.64 gm.	29.79 gm.
" digested	"	... ..	30.03 "	27.88 "
Ether extract digested	per day from basal ration,			
assuming 62 % digestibility	... ..		14.89 "	14.89 "
Bran ether extract digested	per day	15.14 "	12.99 "
" "	digestion coefficients	45.00 %	38.60 %

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The values obtained in the repeat trial, whilst not possessing the abnormal character of those resulting from the first trial, are still remarkably low compared with results given by earlier workers on bran digestibility, and it was deemed advisable to make an investigation of the nature of the ether soluble constituents of the faeces collected in the bran periods, with a view to throwing light on the reasons for this abnormal fat assimilation. The results of this investigation will be given later.

Table IX. *Summary of digestion coefficients obtained in bran trials*
(mean for two sheep).

	Basal ration %	Ordinary bran %	Broad bran %	Results from Kellner*
Dry matter	63.0	57.0	57.9	—
Organic matter	65.3	60.9	61.6	69.0
Crude protein	64.0	72.3	75.3	79.0
Ether extract	62.0	—	—	71.0
N-free extractives	66.1	70.8	69.6	71.0
Crude fibre	65.1	22.7	27.6	26.0
Ash	33.5	—	7.7	—
Crude protein (corrected)	83.6	87.0	88.3	—

* Mean results of 71 investigations of the digestibility of bran. The wide range of variation obtained in these numerous trials is exemplified by the figure for the digestibility of the organic matter, which is the average value of results varying between 61 % and 85 %.

Leaving out of consideration the abnormal results for fat and ash, it will be noted that the digestion coefficients for the dry matter, organic matter, crude protein and carbohydrates of the ordinary bran and the broad bran display remarkable similarity, leading to the conclusion that there is little to choose between the two brans from the feeding point of view. The fibre of broad bran appears to be a little more digestible than that of the ordinary bran, but the order of digestibility is the same in both cases. The main results are also in harmony with the average figures given by Kellner.

If the digestion coefficient of bran fat be assumed to have the value of 71 per cent., then the amounts of digestible nutrients in the two brans are as follows:

Table X. *Amounts of digestible nutrients in ordinary bran and broad bran.*

	Ordinary bran	Broad bran
Crude protein	12.52 %	12.69 %
Ether extract	3.15	3.26
N-free extractives	42.98	41.64
Crude fibre	2.47	3.27
Maintenance starch equivalent per 100 lb. dry fodder	68.35	68.27
Production starch equivalent per 100 lb. dry fodder	49.20	49.09
Nutritive ratio	4.19	4.12

The above results very clearly substantiate the conclusion arrived at, namely, that the two brans are equal from the feeding point of view, and that unless other reasons can be brought forward, there seems little justification for the higher price charged for the broad bran.

Table XI. *Records of nitrogen balances during bran trials.*

Period		N consumed per day gm.	N voided			Mean daily N balance gm.
			In faeces gm.	In urine gm.	Total gm.	
Basal:	Sheep I	11.96	4.38	8.34	12.72	- 0.76
	Sheep II	11.96	4.24	9.95	14.19	- 2.23
Ordinary bran:	Sheep I	26.42	8.27	13.39	21.66	+ 4.76
	Sheep II	26.42	8.36	15.04	23.40	+ 3.02
Broad bran:	Sheep I	25.88	7.50	13.26	20.76	+ 5.12
	Sheep II	25.88	8.00	16.89	24.89	+ 0.99

5. INVESTIGATION OF THE ABNORMAL RESULT FOR DIGESTIBILITY OF BRAN FAT.

It is now well established that the determination of the total ether extract in faeces does not enable exact conclusions to be drawn with regard to the utilisation of the fat consumed in the food. The faeces obtained when an animal is in the fasting condition contain a considerable amount of ether soluble material, and though our knowledge concerning the precise nature of these products is not complete, yet the presence of not only neutral fats and fatty acids, but also substances of the nature of lecithin, cholesterol, cholic acid, etc., has been demonstrated with certainty.

It follows that the ether extract of normal faeces contains not only unassimilated food fat, but also products of a metabolic nature such as those cited above, and under certain circumstances the amount of the latter may exceed that of the fat arising from the actual food residues. If foodstuffs deficient in fat are fed it may happen that more "fat" appears in the faeces than was consumed. The amount of lecithin in faeces under normal circumstances is extremely small. In certain pathological conditions, notably in cases where the pancreas fails to function, lecithin may appear in considerable amount in the faeces. The acids of the bile secretion, taurocholic and glycocholic acids, are rarely present in the faeces as such, but their degradation product, cholic acid, is a regular constituent. It only occurs in traces, however, in normal faeces.

In view of the foregoing it was necessary to investigate in some detail the nature not only of the ether extract of the faeces obtained in the

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bran trials, but also that of the bran itself, in order to decide whether the ether soluble materials of the faeces owed their origin to non-assimilated bran fat or to the accumulation of products of a metabolic nature arising from secretions into the digestive tract.

A weighed amount of the bran ether extract was saponified in the usual manner with alcoholic soda. After removal of alcohol in the water bath, the residue was taken up with hot water. The aqueous extract, which possessed a brilliant red colour, was cooled and extracted twice with ether. This treatment did not remove the red pigment, the latter being precipitated along with fatty acids on acidifying the aqueous solution. The ethereal solution was allowed to evaporate and the residue consisted of clusters of long thin needles, which gave the well-known chloroform-sulphuric acid test for the phytosterol group. The unsaponifiable residue of the bran fat, which amounted to 7.9 per cent. of the total ether extract, was thus a phytosterol, probably sitosterol, since the latter has been shown to occur in the unsaponifiable matter of the oils of wheat.

It follows that the bulk of the bran ether extract (92 per cent.) consists of saponifiable fat, and consequently it would be anticipated that bran fat would readily be digested and absorbed from the alimentary canal.

About 1 gm. of the ether extract of Sheep I faeces collected in the ordinary bran trial was next saponified with alcoholic soda. After removal of alcohol the residue was dissolved in boiling water. On cooling the whole of the solution set to a thick grey-coloured jelly. The mucilaginous material was shown to consist of the sodium salts of palmitic and stearic acids. It is well known that the alkaline salts of these acids dissociate at higher temperatures in dilute aqueous solution. If, for instance, sodium palmitate be dissolved in 900 parts of hot water, the acid salt $\text{NaC}_{16}\text{H}_{31}\text{O}_2 + \text{C}_{16}\text{H}_{32}\text{O}_2$ separates out on cooling. Lewkowitsch (3) states that the alkaline salts when boiled with water give clear solutions which solidify on cooling to a mucilaginous mass.

When a little of the gel obtained in the manner described above was shaken with addition of water, a soap-like solution was obtained which readily foamed. On warming, the liquid became clear, but on cooling, the material once more separated in the gelatinous form. The gel was insoluble in ether, but on acidification it readily lost its gelatinous appearance, giving rise to a substance which was easily and completely soluble in ether. This behaviour clearly indicated that the gel consisted of sodium salts of organic acids.

On remaining in contact with ether, the material lost its mucilaginous character. It was then filtered off and washed well with ether in order to remove unsaponifiable material. After acidifying the mass of sodium salts with dilute sulphuric acid, the resulting organic acids were extracted by means of ether. The ethereal extract was evaporated and the yellowish brown residue was dissolved in alcohol and decolorised by boiling a short time with animal charcoal. The clear alcoholic filtrate was diluted somewhat with distilled water and on cooling a white crystalline substance separated out. This was further crystallised from dilute alcohol and was found to contain neither nitrogen nor sulphur. It possessed a melting point of 56–61° C. (M.P. of a mixture of equal parts of palmitic and stearic acids = 57° C. approx.).

It follows that saponification of the faecal ether extract gives rise to a mixture of the sodium salts of stearic and palmitic acids. Cholalic acid is ruled out on account of its high melting point (M.P. of cholalic acid = 198° C.).

Another portion of the ether extract was investigated quantitatively with the following results:

Unsaponifiable residue: Crystallised readily from alcohol and gave the chloroform-sulphuric acid test for cholesterol and allied substances. It consisted probably of cholesterol mixed with the phytosterol from the bran. It amounted to 19.5 per cent. of the total ether extract of the faeces.

The organic acids recovered from the insoluble sodium salts after saponification amounted to 66.2 per cent. of the total ether extract. In addition, a small amount of sodium salts of organic acids remained dissolved after filtering off the undissolved sodium salts.

In coming to a final decision as to the nature of the ether extract of the faeces, three possibilities had to be considered:

1. The presence of a large amount of free fatty acids in the faeces.
2. The presence of a large amount of neutral fat.
3. The presence of a large amount of lecithin, which on saponification of the ether extract would give rise to sodium salts of fatty acids. Such a state of affairs would, however, be very abnormal.

In order to ascertain whether lecithin was present to any appreciable extent, 1 gm. of the ether extract of the faeces was fused with fusion mixture, and the residue, after cooling, was extracted with warm dilute nitric acid, filtered and the filtrate tested for phosphate. No yellow precipitate was obtained with ammonium molybdate reagent and the test was repeated on another portion of the ether extract with the same

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result. It was therefore concluded that the faeces contained little or no lecithin.

A further weighed portion of the ether extract was next dissolved in a neutral ether-alcohol mixture and titrated with $N/10$ NaOH, using phenolphthalein as indicator. The following result was obtained:

0.3219 gm. of ether extract required 6.8 c.c. $N/10$ NaOH (calculated in terms of stearic acid = 0.1930 gm. stearic acid). The presence of sodium salts in the solution after titration was demonstrated by shaking out the neutralised liquid with water and acidifying the aqueous extract, when the fatty acids were precipitated.

A further confirmation of the presence of free fatty acids in the faeces was obtained by boiling the alcoholic solution of the ether extract with animal charcoal, filtering and allowing the filtrate to crystallise out.

0.28 gm. of the crystalline substance required 7 c.c. $N/10$ NaOH for neutralisation in ether-alcohol solution (= 0.20 gm. stearic acid). The endpoint in this titration was much easier to determine with exactitude than that associated with the titration of the crude ether extract.

It was concluded on the grounds of the above results that about 60 per cent. of the ether extract of the faeces collected from Sheep I in the ordinary bran experiment consisted of a mixture of the free fatty acids, stearic and palmitic. In other words, Sheep I was excreting each day throughout this trial approximately 22 gm. of a mixture of these acids.

The ether extract of the faeces from Sheep I during the repeat trial on the second sample of ordinary bran was investigated in a similar manner, and it was found that 53.3 per cent. of the total ether soluble constituents consisted of free fatty acids (calculated in terms of stearic acid). During this trial, therefore, Sheep I was excreting daily about 15 gm. of free fatty acids.

It may thus be inferred that the abnormal results obtained in connection with bran fat assimilation during all the trials in which bran was employed arise from the exceptionally large excretion of free fatty acids in the faeces. This abnormal behaviour points to a partial breakdown of the bile function. The fat constituent of the food appears to have undergone hydrolysis by the action of the steapsin of the pancreatic secretion, but the resulting fatty acids have escaped emulsification and neutralisation by the bile. Absorption of the fatty acids from the digestive tract has therefore not taken place and the consequence has been the appearance of large amounts of these substances in the faeces.

It was distinctly observable that the sheep did not thrive very well on the bran diets and the faeces contained a fair proportion of coagulated,

and sometimes slightly blood-stained, mucus. The fatty acids, however, did not arise from this constituent, as 11.2 gm. of the material, carefully separated from the faeces, was thoroughly extracted with ether and yielded only 0.087 gm. (0.8 per cent. approx.) of ether soluble substances, the nature of which resembled very closely that of the ether extract of the whole sample of faeces.

An extremely interesting feature of the trials is the fact that although the process of digestion and absorption of the fat suffered a serious breakdown, yet the mechanisms whereby the other ingredients of the bran were digested appear to have been entirely unaffected, since the values of the digestion coefficients of the bran nutrients other than fat displayed quite good agreement with the average figures given by Kellner. This lends support to the supposition that a disturbance of the digestion of any single ingredient of a foodstuff is possible without the digestion and assimilation of the other constituents being affected to any material extent.

That this abnormal behaviour is not to be associated with any peculiarities in the bran itself, but is rather to be regarded as an unfortunate individual characteristic of the sheep under experiment, is suggested not only by the fact that successful determinations of bran fat digestibility have been made in earlier German investigations, but also by the result already alluded to, namely, that the ability of the sheep to assimilate the fat of the linseed cake-meadow hay basal diet had undergone a marked diminution since the carrying out of a similar trial on the same basal ration about eighteen months previous to the time of the present trials. An examination of the ether extract of the faeces from Sheep I during the basal period showed that about 14.5 per cent. of it consisted of free fatty acids. This corresponded with an average daily excretion of about 1.2 gm. free fatty acids even on the simple hay-cake diet.

The sheep employed in this trial have been on experimental diets at various intervals since the beginning of 1921, at which date they were already at a mature age. The results of this investigation suggest that, with increasing age, the power of the sheep to assimilate the fat ingredient of the food becomes weaker, and this is evidenced by a corresponding increase in the excretion of free fatty acids in the faeces. The point comes out strikingly in the present series of experiments and certainly warrants further investigation by the physiologist, especially if, as appears possible, the results are capable of interpretation into terms of human nutrition.

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6. DIGESTIBILITY OF MIDLINGS AND FINE MIDLINGS.

For the purposes of the middlings feeding trial a large composite sample was made up, representative of the 28 samples in group E and the two samples in group F. The whole sample was thoroughly mixed up in a suitable machine.

The sample of fine middlings was prepared so as to be representative of the finest offals obtained from the three firms conducting business in South Wales and South Devon.

The general arrangement of the experiment was the same as that already described in connection with the bran trials, with the exception that the basal diet was increased to 500 gm. chaffed meadow hay + 150 gm. linseed cake. The amount of foodstuff added on to this daily ration was 600 gm. in both middlings and fine middlings periods. The same two sheep were used.

The essential data are given in the following tables:

Table XII. *Composition of foodstuffs* (calculated to dry matter basis).

	Meadow hay	Linseed cake	Middlings	Fine middlings
	%	%	%	%
Crude protein ...	9.48	31.20	18.38	19.64
Ether extract ...	4.28	12.51	5.67	4.83
N-free extractives	47.53	38.13	66.05	70.16
Crude fibre ...	32.56	9.85	5.69	2.62
Ash ...	6.15	8.31	4.21	2.75
Mean dry matter of hay		throughout trial	% 86.33	
" "		linseed cake	" 88.45	
" "		middlings	" 86.00	
" "		fine middlings	" 86.75	

Table XIII. *Average daily weight and composition of faeces.*

	Basal period		Middlings period		Fine middlings period	
	Sheep I	Sheep II	Sheep I	Sheep II	Sheep I	Sheep II
	gm.	gm.	gm.	gm.	gm.	gm.
Mean weight of fresh faeces daily	606.0	457.0	1483.0	1301.0	1256.0	907.0
" " dry matter "	244.9	227.3	390.3	375.6	384.3	339.8

Composition of dry matter.

	Sheep I	Sheep II	Sheep I	Sheep II	Sheep I	Sheep II
	%	%	%	%	%	%
Crude protein* ...	12.22	12.01	14.65	13.11	14.67	14.05
Ether extract ...	3.76	3.83	7.44	5.84	6.86	5.95
N-free extractives ...	43.38	43.57	41.89	43.30	43.09	44.65
Crude fibre ...	29.87	28.72	22.12	24.66	23.54	23.77
Ash ...	10.77	11.87	13.90	13.09	11.84	11.58
Pepsin-HCl insoluble protein	5.88	6.26	6.35	6.06	6.35	6.64

* Nitrogen as determined on fresh faeces	0.801	0.941	0.618	0.637	0.743	0.917
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Table XIV. *Digestibility of basal ration.*

Daily ration: 500 gm. meadow hay + 150 gm. linseed cake.

Sheep I.

			Total dry matter gm.	Organic matter gm.	Crude protein gm.	Ether extract gm.	N-free extrac- tives gm.	Crude fibre gm.	Ash gm.
Consumed:									
Meadow hay	...	...	431.70	405.15	40.93	18.48	205.18	140.56	26.55
Linseed cake	...	...	132.70	121.67	41.40	16.60	50.60	13.07	11.03
Total	...	...	564.40	526.82	82.33	35.08	255.78	153.63	37.58
Voided	...	...	244.90	218.52	30.34*	9.21	106.23	73.15	26.38
Digested	...	...	319.50	308.30	51.99	25.87	149.55	80.48	11.20
Digestion coefficients, %	...	...	56.61	58.50	63.15	73.75	58.47	52.38	29.80

Sheep II.

Consumed (as above)	...	...	564.40	526.82	82.33	35.08	255.78	153.63	37.58
Voided	...	...	227.30	200.32	26.88*	8.71	99.03	65.28	26.98
Digested	...	...	337.10	326.50	55.45	26.37	156.75	88.35	10.60
Digestion coefficients, %	...	...	59.73	61.98	67.35	75.17	61.28	57.51	28.21
Mean digestion coefficients, %	...	...	58.20	60.30	65.30	74.50	59.90	54.90	29.00

* Calculated on nitrogen of *fresh* faeces.*Protein digestibility corrected for metabolic nitrogen.*

	Sheep I	Sheep II
Protein consumed, gm.	82.33	82.33
Pepsin-HCl insoluble protein voided, gm.	14.40	14.23
Protein digested, gm.	67.93	68.10
Corrected digestion coefficients, %	82.51	82.71
Mean corrected digestion coefficient, %	82.60	

The results for the basal diet of hay and cake indicate that during this period there was no such disturbance of the digestion and utilisation of fat as was noticed in the bran periods. The digestion coefficient for the fat attained the satisfactory value of 74 per cent.

Owing to the fact that the fibre of the middlings and fine middlings formed such a small proportion of the total fibre of the rations (in the case of fine middlings less than 14 gm. in a total of 167 gm.), it followed that the results expressing the digestibility of the fibre constituent must at the best be exceedingly unreliable. In view of these circumstances it was deemed more satisfactory to class together the N-free extractives and fibre under the heading of carbohydrates (see Tables XV and XVI).

Comments on Tables XV and XVI.

It will be noted that the fat digestion coefficients for both sheep in both the middlings and fine middlings trials are very low, this being again due to a partial breakdown of the mechanism for digestion and absorption of fat, leading to an excessive excretion of fatty acids. The

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disturbance appears to have been more pronounced with Sheep I than with Sheep II. It is further of interest to note that in every case the non-absorption of fat has led to a decided increase in the amount of inorganic salts appearing in the faeces.

For the purposes of calculating the amount of digestible nutrients in the foodstuffs it has been necessary to employ the following fat digestion coefficients as recorded by Wood (4).

Middlings fat ...	86.0 %
Fine middlings fat ..	88.3 ..

Table XV. *Digestibility of middlings.*

Daily ration: 500 gm. meadow hay + 150 gm. linseed cake + 600 gm. middlings.

Sheep I.

		Total dry matter gm.	Organic matter gm.	Crude protein gm.	Ether extract gm.	Carbo- hydrates*	Ash gm.
Consumed:							
Meadow hay ...	...	431.70	405.15	40.93	18.48	345.74	26.55
Linseed cake ...	...	132.70	121.67	41.40	16.60	63.67	11.03
Middlings... ..	...	516.00	494.28	94.84	29.26	370.18	21.72
Total ...	...	1080.40	1021.10	177.17	64.34	779.59	59.30
Voided (total) ...	...	390.30	336.05	57.25†	29.04	249.83	54.25
From basal ration ...	...	244.90	218.52	30.34	9.21	179.38	26.38
From middlings ...	...	145.40	117.53	26.91	19.83	70.45	27.87
Digested from middlings ...	...	370.60	376.75	67.93	9.43	299.73	—
Digestion coefficients, % ...	...	71.82	76.22	71.63	32.23	80.97	—

Sheep II.

Consumed (as above) ...	...	1080.40	1021.10	177.17	64.34	779.59	59.30
Voided (total) ...	...	375.60	326.44	51.75†	21.94	255.26	49.16
From basal ration ...	...	227.30	200.32	26.88	8.71	164.31	26.98
From middlings ...	...	148.30	126.12	24.87	13.23	90.95	22.18
Digested from middlings ...	...	367.70	368.16	69.97	16.03	279.23	—
Digestion coefficients, % ...	...	71.26	74.48	73.78	54.78	75.43	—
Mean digestion coefficients, %	...	71.50	75.40	72.70	43.50	78.20	—

* Including fibre.

† Calculated on nitrogen of *fresh* faeces.

Protein digestibility corrected for metabolic nitrogen.

	Sheep I	Sheep II
Protein consumed, gm. ...	94.84	94.84
Total pepsin-HCl insoluble protein voided, gm.	24.78	22.76
From basal ration, gm. ...	14.40	14.23
From middlings, gm. ...	10.38	8.53
Digested from middlings, gm. ...	84.46	86.31
Corrected digestion coefficients, %	89.06	91.00
Mean corrected digestion coefficient, %	90.00	

Table XVI. *Digestibility of fine middlings.*

Daily ration: 500 gm. meadow hay + 150 gm. linseed cake + 600 gm. fine middlings.

Sheep I.

		Total dry matter gm.	Organic matter gm.	Crude protein gm.	Ether extract gm.	Carbo- hydrates*	Ash gm.
Consumed:							
Meadow hay	... ..	431.70	405.15	40.93	18.48	345.74	26.55
Linseed cake	... ..	132.70	121.67	41.40	16.60	63.67	11.03
Fine middlings	... ..	520.50	506.19	102.23	25.14	378.82	14.31
Total	... ..	1084.90	1033.01	184.56	60.22	788.23	51.89
Voided (total)	... ..	384.30	338.80	58.31†	26.36	256.06	45.50
From basal ration	... ..	244.90	218.52	30.34	9.21	179.38	26.38
From fine middlings	... ..	139.40	120.28	27.97	17.15	76.68	19.12
Digested from fine middlings	...	381.10	385.91	74.26	7.99	302.14	—
Digestion coefficients, %	...	73.22	76.24	72.64	31.78	79.76	—

Sheep II.

Consumed (as above)	... ..	1084.90	1033.01	184.56	60.22	788.23	51.89
Voided (total)	... ..	339.80	300.45	52.00†	20.22	232.49	39.35
From basal ration	... ..	227.30	200.32	26.88	8.71	164.31	26.98
From fine middlings	... ..	112.50	100.13	25.12	11.51	68.18	12.37
Digested from fine middlings	...	408.00	406.06	77.11	13.63	310.64	1.94
Digestion coefficients, %	...	78.38	80.22	75.43	54.22	82.00	13.60
Mean digestion coefficients, %	...	75.80	78.20	74.00	43.00	80.90	—

* Including fibre.

† Calculated on nitrogen of *fresh* faeces.*Protein digestibility corrected for metabolic nitrogen.*

	Sheep I	Sheep II
Protein consumed, gm.	102.23	102.23
Total pepsin-HCl insoluble protein voided, gm.	24.40	22.56
From basal ration, gm.	14.40	14.23
From fine middlings, gm.	10.00	8.33
Digested from fine middlings, gm.	92.23	93.90
Corrected digestion coefficients, %	90.22	91.85
Mean corrected digestion coefficient, %	91.00	

Table XVII. *Summary of nitrogen balances during middlings trials.*

		N voided per day			Mean daily N balance gm.
Period		N consumed gm.	In urine gm.	In faeces gm.	
Basal:	Sheep I	13.17	7.90	4.85	+0.42
	Sheep II	13.17	8.68	4.30	+0.19
Middlings:	Sheep I	28.34	14.13	9.16	+5.05
	Sheep II	28.34	15.94	8.28	+4.12
Fine middlings:	Sheep I	29.53	17.26	9.33	+2.94
	Sheep II	29.53	17.88	8.32	+3.33

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7. FINAL TABLES AND CONCLUSIONS.

A. *Summary of digestion coefficients.*

	Broad bran %	Ordinary bran %	Middlings %	Fine middlings %
Dry matter ...	57.9	57.0	71.5	75.8
Organic matter ...	61.6	60.9	75.4	78.2
Crude protein ...	75.3	72.3	72.7	74.0
Protein (corrected)	88.3	87.0	90.0	91.0
Ether extract ...	71.0	71.0	86.0	88.3
Carbohydrates* ...	62.7	63.5	78.2	80.9

* Including fibre.

B. *Amounts of digestible nutrients and feeding values.*

	Broad bran %	Ordinary bran %	Middlings %	Fine middlings %
Crude protein... ..	12.69	12.52	13.36	14.53
Ether extract... ..	3.26	3.15	4.88	4.26
Carbohydrates* ...	44.91	45.45	56.10	58.88
Maintenance starch equivalent† (lb.)	68.27	68.35	84.02	86.84
Production starch equivalent† (lb.)	49.09	49.20	67.95	79.12
Nutritive ratio	4.12	4.19	5.02	4.71

* Including fibre.

† Per 100 lb. dry foodstuff.

The results in so far as they affect the comparison between broad bran and ordinary bran have already been discussed in detail.

The figures in Table A for dry matter, organic matter, ether extract and carbohydrates show clearly a progressive increase in the digestibility of these constituents with decrease in the size of particles constituting the offals.

This behaviour, however, is not displayed in the case of protein digestibility, and there can be little doubt that the protein of bran is almost as digestible as the protein of middlings and fine middlings.

Table B gives data which emphasise the statement made earlier in this communication, namely, that a simple uniform method of grading offals on the basis of size of particles yields grades which are characterised by a perfectly distinctive chemical composition (both in regard to crude and digestible constituents) and also by the possession of well-defined feeding values.

The values of the starch equivalents are throughout higher than those attributed on somewhat speculative grounds to wheat offals by Wood and Adie. The latter investigators did not possess at the time any reliable digestibility data on which to base their calculations.

Attention should be directed to the excellent feeding value possessed by the fine middlings. From the feeder's point of view it is to be regretted that so little of this class of offals is made in this country at the present time.

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